icdp

INTERNATIONAL
CONTINENTAL SCIENTIFIC
DRILLING PROGRAM

UNRAVELLING THE WORKINGS OF PLANET EARTH

SCIENCE PLAN FOR 2014–2019

We invite you to think about why Earth Science matters, and the often surprising ways in which it affects our lives.

UNRAVELLING THE WORKINGS OF PLANET EARTH
SCIENCE PLAN FOR 2014–2019

EXECUTIVE SUMMARY

Earth science goals

Modern earth science has two basic goals: seeking to unravel the historical archives that are locked up in rocks formed over the entire history of the Earth, and understanding the structure and dynamics of the active planet on which we live. To realise both goals scientific drilling is essential: it uncovers rock archives containing the records of tectonic, climatic and biological cycles, and impacts from extraterrestrial bodies, from the present day, back into deep time. Targeted scientific drilling allows us to sample, measure and monitor the Earth to help develop sustainable resources. Drillhole observatories give key insights into Earth's internal dynamic activities, such as fluctuations in heat and the magnetic fields or earthquakes and volcanoes.

It would be impossible to undertake modern earth science research without scientific drilling. The International Continental Scientific Drilling Program (ICDP) has played a primary role over the past two decades, uncovering geological secrets from beneath the continents. It has enabled first-class science to be pursued, targets to be probed and hypotheses to be tested, with the result that fundamental discoveries about 'System Earth' have been made, often bringing added-value socio-economic benefits.

The programme

ICDP boasts a strong and active participation of twenty-two member nations. It has undertaken more than 30 drilling projects and run 75 workshops. Its current budget of $3.5 million a year is but a small fraction of that of the Integrated Ocean Drilling Programme (IODP) or other large earth science infrastructure projects. ICDP —already lean and mean with a minimum of bureaucratic ballast—is making landmark changes to its operational activities to build an even stronger technical base and reshaping its management structure. Networking activities with other major earth science programmes are being streamlined, and stronger bridges with the private and government sector built, thus strengthening ICDP's economic and social portfolio.

The spectrum

ICDP has a broad portfolio centred on scientific drilling. Firstly, it provides a strategy for successful science delivery by funding workshops, leading and supporting technological innovation, conducting outreach and teaching programmes and actively cooperating with programmes such as IODP. It provides co-funding for coring as well as advising on all matters technical and logistical. It offers technological support for geophysical logging and data management. ICDP has the advantage of being able to

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.

mobilise multiple drilling platforms in quite diverse environments: from lake sediment drilling for records of climate change over the past thousands of years, to high technology for drilling into high-temperature hydrothermal systems and micro-sampling for fluids using sterilised drill-core sampling systems. Public outreach and teaching are strong components of ICDP's profile, and will be expanded further. ICDP can make a significant difference in educating the public about our subsurface, providing confidence that we know enough about the upper kilometres in order to provide resilient solutions to infrastructure and resource development. A strong education programme will inspire young scientists and help create the next generation of scientists who will be needed to specialise in geology, geophysics, geochemistry and geomicrobiology.

Process scales

The Earth's fundamental processes work on timescales from microseconds, exemplified by stress transfer during a fault rupturing, to hundreds of millions of years for plate tectonic cycles. The same is true of length, breadth and depth, from sub-micron bio-films and mineral defects, to thousands of kilometres in fault movements, basin-filling and mountain-building processes. The interconnectivity of processes, including feedbacks, amplifications and degrees of organisation between them, is staggeringly complex, involving chemical, physical and biological components. Scientific drilling has made many fundamental discoveries with individual drill holes, but the coordination of targeted activities is a key element in understanding spatial and temporal variability, and the interconnectivity of systems. This is an organisational challenge facing all drilling organisations.

The science plan

This document, constituting the third ICDP Science Plan, came about by engaging the science base around the theme of 'Unravelling the workings of Planet Earth'. It lays out some of the big questions that confront the earth sciences and suggests solutions that can be achieved by scientific drilling. Some of these questions are fundamental, for instance, the origin of life on Earth, whereas others use the past history of the Earth to imagine what a future Earth might look like. Some drilling applications are highly specialised, such as that for developing sensor networks in underground observatories to monitor earthquakes and volcanoes, the latter underpinning energy production. To varying extents, these scientific programmes have objectives that are shared with the energy sector, water, insurance, mining and other industries, and with government objectives, but ICDP is firmly entrenched as a research enabler always focused on cutting edge science questions and innovations.

The main themes in this document are:

- active faults and earthquake processes
- heat and mass transfer
- global cycles, and
- the hidden biosphere
- cataclysmic events

These will underpin societal challenges in:

- water quality and availability
- climate and ecosystem evolution
- energy and mineral resources and
- natural hazards.

We cordially invite you to read this White Paper. You will discover why earth science matters, and uncover the many surprising ways in which it affects your everyday life.

ICDP—WHO WE ARE AND WHAT WE DO

Figure 1. ICDP's commingled funding principle.

Our mission

ICDP is the international platform for scientific research drilling in continental settings. Founded in 1996, its mission is to explore the Earth's subsurface so that its structure and workings are unfolded.

Our offer

ICDP is an infrastructure for scientific drilling. It provides financial and logistical assistance for leading international teams of earth scientists to investigate sites of global geological significance. The financial assistance on offer is for the drilling programme itself, and not for the scientific investigations that follow. Commingled funding is the name of the game—we encourage and assist the scientists in gathering funding, but do not take on full sponsorship. A key element provided by ICDP in addition to pecuniary funds is operational support—the sharing of technical and logistical know-how and the provision of operational personnel and equipment is unique in scientific drilling organisations. In a nutshell, ICDP is an enabler, committed to putting excellent scientific ideas into best practice.

The base

ICDP brings together scientists and funding agencies from 22 nations and one organisation (UNESCO) to work together at the highest scientific and technical level in order to collectively grant funding and implement logistical support. More than 30 drilling projects and 75 planning workshops have been supported to date. The programme has an average annual budget of $3.5 million from membership contributions.

Benefits

What are the benefits of the programme for its sponsors? To secure ICDP funding, all projects must, fulfil rigorous selection criteria, one of which is, addressing modern societal challenges, be it the protection against natural disasters ('natural hazards'), unravelling past climate change ('climate and ecosystems'), or serving an ever-growing population with natural resources ('sustainable georesources'). ICDP projects always have this element of added value.

The science plan

ICDP is not a science funding body but nevertheless chooses to lay out the key research challenges in the coming years by commissioning a science plan. This plan acts as a roadmap for the international earth science community and at the same time serves as a docking station for national funding initiatives. This White Paper, 'Unravelling the workings of Planet Earth', is a strategy document laying out the major scientific challenges for the period 2014–2019. It is the third of its kind in the history of ICDP: the first was published shortly after the foundation of the programme in 1996 (Zoback and Emmermann, 1996) and the second roughly ten years later (Harms et al., 2007). Running in parallel to the current science plan is a special issue of the *International Journal of Earth Sciences* in order to provide a snapshot of the scientific investigations currently underway that are directly tied with drilling investigations.

Figure 2. ICDP at the COSC drill site, Sweden.

QUO VADIS, ICDP?

Figure 3. On-site participants, ICDP Science Conference 2013

The ICDP science conference 'Imaging the Past to Imagine our Future', was convened in Potsdam, Germany, 11–14 November, 2013. One hundred and sixty-four invited attendees from 29 countries took part on-site—from early career dynamos to acknowledged experts—representing the full palette of earth science disciplines, with many more participating via live streaming from the geoscience world at large.

The conference's overall aim was to debate the best way forward for ICDP over the next five years. The science plan took shape by dovetailing scientific goals with societal (socio-economic) challenges. The conference was also used to strengthen and expand ties with member countries, consider how to best incorporate industry into ICDP (a science-driven organisation), and to instigate new measures for a better gender balance in its panels and committees.

CONFERENCE ACKNOWLEDGEMENTS

Our sincere thanks go out to those who have contributed their valuable time, boundless energy and creative ideas to the conference and the White Paper.

Presenters, discussion leaders

Flavio Anselmetti,
Jean-Philipp Avouac,
Keir Becker,
Marco Bohnhoff,
Eduardo de Mulder,
Donald Dingwell,
William Ellsworth,
Guðmundur Ómar Friðleifsson,
Ulrich Harms,
Steve Hickman,
Brian Horsfield,
Roy Hyndman,
Jens Kallmeyer,
Tom Kieft,
Christian Koeberl,
Ilmo Kukkonen,
Steve Larter,
Ralf Littke,
John Ludden,
Stefan Luthi,
Jim Mori,
John Shervais,
Lynn Soreghan,
Jim Russell,
Alexander van Geen,
Jim Whitcomb,
Thomas Wiersberg

White Paper contributions

Nicholas Arndt,
Keir Becker,
Marco Bohnhoff,
Achim Brauer,
Philippe Claeys,
Andrew Cohen,
Georg Dresen,
William Ellsworth,
Guðmundur Ómar Friðleifsson,
Ulrich Harms,
Brian Horsfield,
Hans-Wofgang Hubberten,
Ernst Huenges,
Roy Hyndman,
Jens Kallmeyer,
Tom Kieft,
Carola Knebel,
Christian Koeberl,
Achim Kopf,
Ilmo Kukkonen,
Ralf Littke,
John Ludden,
Volker Lüders,
Stefan Luthi,
Jim Mori,
Karsten Pedersen,
Bernhard Prevedel,
Judith Schicks,
Lynn Soreghan,
Joanna Thomas,
Robert Trumbull,
Jim Whitcomb,
Thomas Wiersberg,
Maarten de Wit

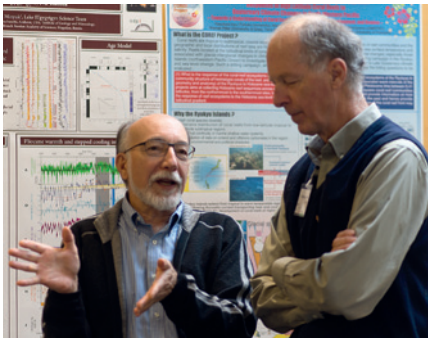


Figure 4. Scientists debating at the poster session.

CHALLENGES FOR SCIENCE AND SOCIETY

Integrating the needs of science and society is a cornerstone of the new science plan …

The challenge

Minimising the risk of natural disasters, supplying an ever growing world population with industrial raw materials, energy, clean drinking water, and addressing the threats posed by global change; these are some of the fundamental challenges facing mankind in the 21st century. *All of these challenges are inextricably linked with the workings of planet Earth, namely the chemical reactions, physical movements and biological interactions taking place within the solid Earth and at interfaces with the hydrosphere, atmosphere and biosphere.*

Predictions

Events such as earthquakes dramatically impinge upon our lives in seconds, minutes and hours, but the root cause is a build-up of stress over thousands of years deep within the crust at distant locations. Predicting exactly where and when such natural hazards will occur is a daunting task, but key advances have already been made by monitoring the stress and strain and fluid flow in the Earth's subsurface using sensitive instrumentation, and by issuing early warnings via integrated earth science infrastructure.

Cycles

Then there is global warming … We need to distinguish the damage inflicted by man, by combusting fossil fuels, for instance, from that induced by the natural cycles that are part and parcel of Mother Earth. Archived records of what has gone before in Earth history are preserved in sedimentary rocks at surprisingly high resolution, and help to unravel the puzzle.

The origins of life itself and the evolution of species lie preserved in the sedimentary record awaiting discovery. Unravelling the links between human habitat, climate and palaeogeography is already underway.

The deep biosphere

When we think of life on present-day Earth, we think of the diversity that is displayed in rain forests and oceans, and in the types of micro-organisms (wanted and unwanted) which live in and amongst us. Intriguingly, there is a biosphere within the pores and cracks of rocks (< about 2 km) that is roughly the same size as the biosphere we know and love. We are only just beginning to understand how this deep biosphere is involved in the natural cycling of elements, and exploring the ways in which we can put this underground system to good use.

All in all, the workings of planet Earth are far from understood; a great many frontiers await modern-day explorers. Scientific drilling provides key insights into all of these processes.

THE EARTH BENEATH OUR FEET— THE DARK UNDERGROUND

Brian Horsfield GFZ—German Research Centre for Geosciences, Germany

We think we know our planet, the Earth. Detailed maps, aerial pictures and satellite images 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 and how can we gain information about this?

Geologists study every road cut, where machines and men with dynamite have exposed the layers of rock normally hidden beneath soil and vegetation. Geophysicists use seismic rays and electromagnetic waves to figuratively peel away the layers of the earth. Geochemists study the rocks which they believe were once part of the interior of the earth. But the plethora of information gathered by all these means leads at best to models and hypotheses about the Earth's interior. The best way to enlighten the dark underworld and to verify our models of Earth is to bring up samples from depths and to obtain data in the dynamic downs.

Drilling is an expensive proposition that rarely a single country can afford due to the enormous costs associated with the logistics. How can researchers justify such costs to a funding agency, if the results are merely scientific and do not gush out a wealth of resources? This is exactly where ICDP comes in. The goal of this pro-gramme is to encourage earth scientists con-sidering drilling as a tool for their research and to make drilling the reality check for the models and ideas developed.

The scientific focus of ICDP for the forthcoming years is laid out in this White Paper to serve as a guideline for continental scientific drilling.

'We want to bring scientific drilling on continents within the reach of every member of the earth science community.'

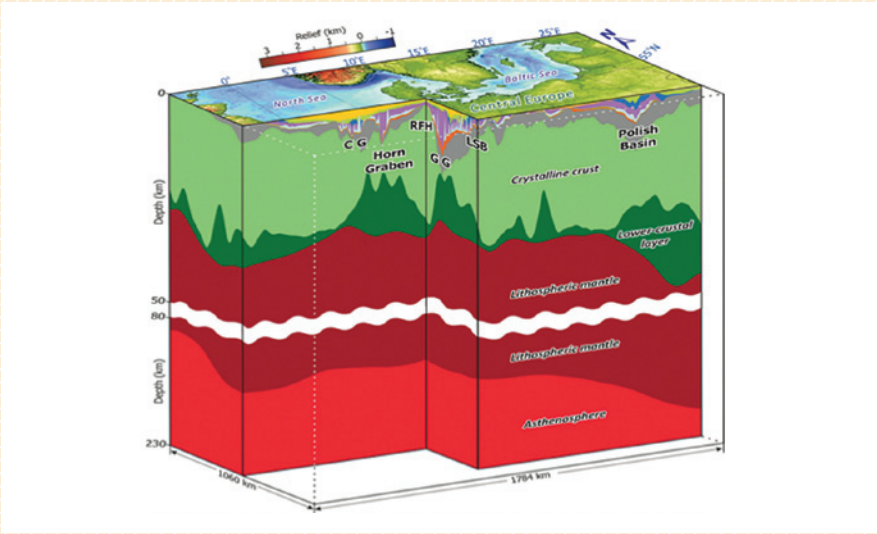


Figure 5. 3D structural model of the Central European Basin System.

SCIENTIFIC DRILLING

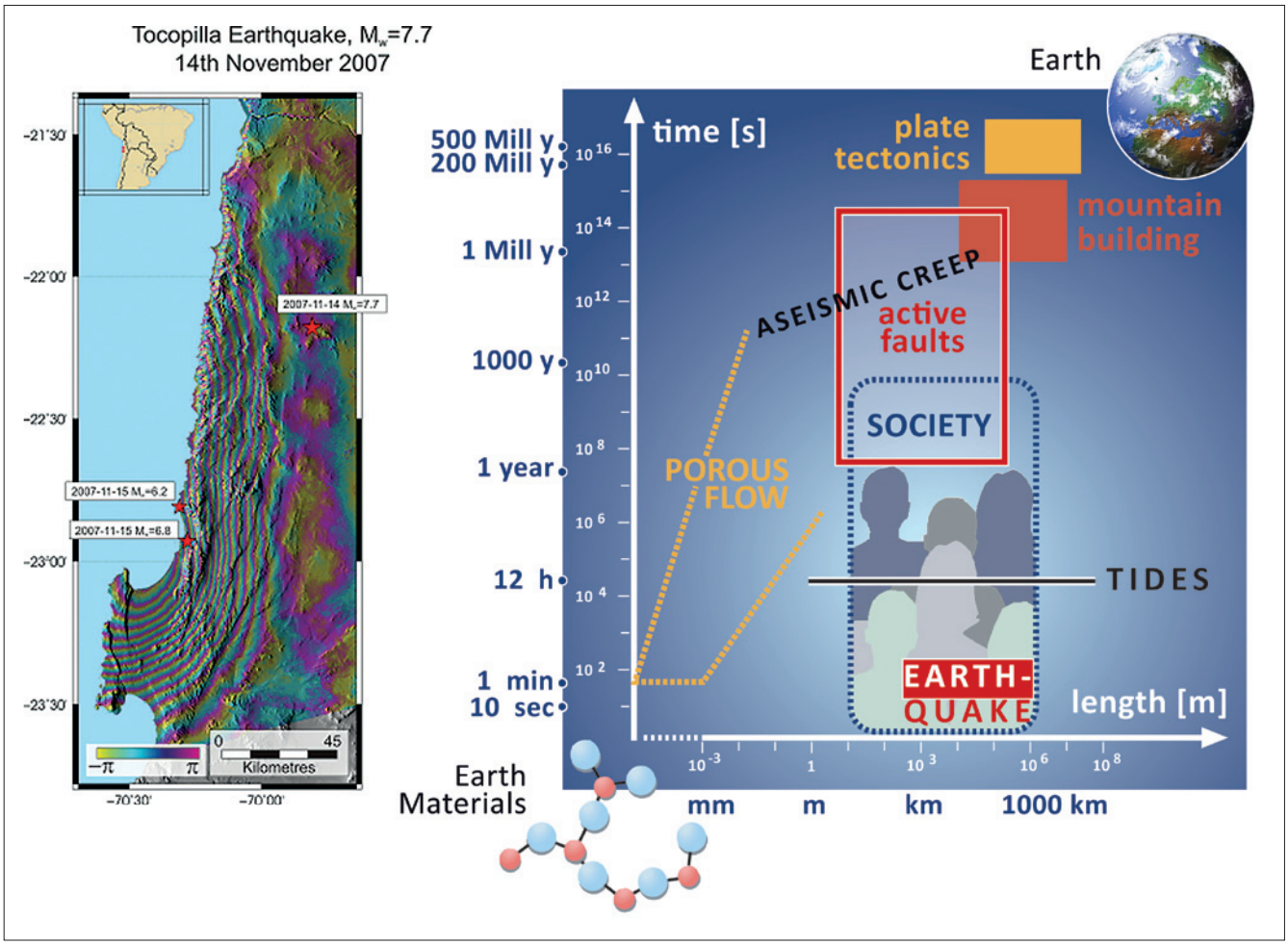


Figure 6. The build-up of stress.

Scientific drilling is an indispensable and unique tool for exploring and unraveling the myriad natural and anthropogenic processes that are part and parcel of 'System Earth'. The precious relicts and living systems it contains need to be probed, collected, monitored and analysed, taking care to choose key sites around the globe.

ICDP is not alone in conducting scientific drilling on a global scale. We are building ever-stronger links between the terrestrial (ICDP) and marine (IODP) realms for the development of concerted actions, extending from involvement in respective science plan definition, through individual project design, to the joint publication of the magazine

Scientific Drilling. Further links with ANDRILL, whose focus is the Antarctic, and the Deep Carbon Observatory, which studies the deep carbon cycle, are also under development. **The pooling and coordinating of our respective actions, whether it be on land, sea or ice, is imperative. The White Paper revisits these issues.**

Scientific drilling has objectives that are broadly shared with the oil and gas, water, insurance, mining and other industries. All are seeking to better understand the workings of 'System Earth'. In the commercial world, it comes down to securing new resources, exploiting known ones, and minimising risk associated with natural hazards and resource development. Scientific drilling remains science-driven, seeking to understand the chemistry, physics and biology in time-space coordinates. It makes sense to explore areas of common interest with industry, for example selected data and sample acquisition. **When managed astutely, pure and applied research go hand in hand to achieve common objectives. The White Paper considers these issues.**

Figure 7. Drill bits at the Alpine Fault drill site, New Zealand

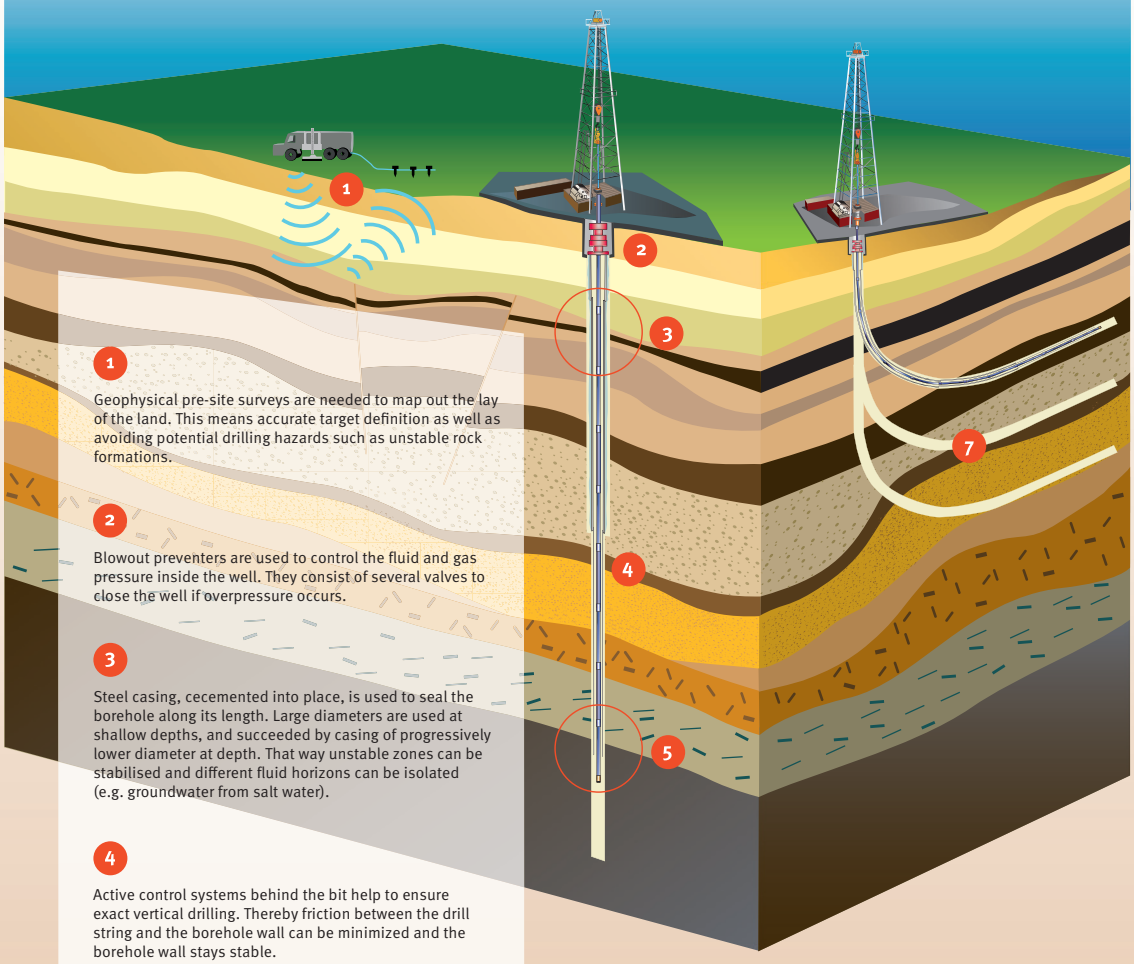
MORE THAN SIMPLY DRILLING HOLES —A STRATEGY FOR SUCCESS

Scientific drilling relies heavily on leading edge technology. But it is way more than that. The ICDP portfolio covers finances, logistics and operational support, and all with **minimal administrative and bureaucratic fuss**. Here is a list of tasks and challenges that are part and parcel of that portfolio:

- Identify world class drilling sites to probe geological targets of global significance.
- Fund workshops to assemble the best possible science teams, define scientific objectives and mesh scientific ideas with practical drilling concepts.
- Provide accountability for sponsors for the programme as a whole, in terms of scientific effectiveness and financial efficiency.
- Secure commingled funding concepts for the effective planning, implementation and execution of a viable strategic programme which meets scientific objectives of socio-economic relevance.
- Identify sites for international cooperation in scientific drilling, and thus to provide cost effective means of answering key scientific questions, in close collaboration with other scientific drilling organisations.
- Ensure that appropriate pre-site surveys are carried out at an early stage in planning.
- Provide operational support for drilling activities, electric logging tools, and sample- and data-management software platforms.
- To ensure appropriate monitoring of the programme and accountability to sponsors in terms of scientific effectiveness and financial efficiency;
- Ensure effective application and dissemination of the results, and to inspire young scientists in particular. ICDP encourages earth science education and facilitates knowledge transfer.

We are striving to improve upon the way we do business by ensuring that each task is conducted efficiently and effectively. The closing chapter of this White Paper looks into how the organisation can be managed better.

Modern technology for scientific drilling: the basic elements



1

Geophysical pre-site surveys are needed to map out the lay of the land. This means accurate target definition as well as avoiding potential drilling hazards such as unstable rock formations.

2

Blowout preventers are used to control the fluid and gas pressure inside the well. They consist of several valves to close the well if overpressure occurs.

3

Steel casing, cecemented into place, is used to seal the borehole along its length. Large diameters are used at shallow depths, and succeeded by casing of progressively lower diameter at depth. That way unstable zones can be stabilised and different fluid horizons can be isolated (e.g. groundwater from salt water).

4

Active control systems behind the bit help to ensure exact vertical drilling. Thereby friction between the drill string and the borehole wall can be minimized and the borehole wall stays stable.

5

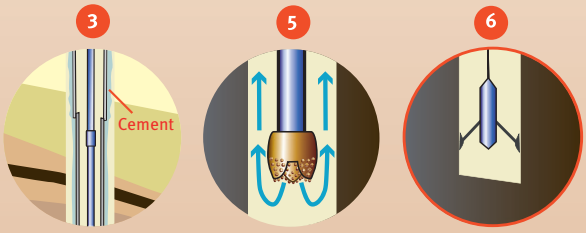
The drilling mud serves many purposes. It discharges cuttings from the bit to the surface and stabilizes the borehole. It also constantly cools the drill bit, reduces friction, drives the downhole motor, and balances differences in pressure. The drilling mud must therefore be monitored and its chemistry and rheology adjusted continuously.

6

Borehole measurements and tests help to characterize rocks and, fluids, thereby maximising safety.

7

Controlled drilled horizontal wells with up to 10 km of deviation and multiple re-entry protocols allow access to distant formations. When drilled along the bedding of a formation, gas and crude oil production efficiency is enhanced.



ICDP projects address a whole host of geological targets from deep to shallow, from tectonically simple to complex, and under very different pressure and temperature conditions. Modern technology ensures all these targets can be reached, even if they lie at 12 km depth! Having said that, costs rise exponentially with depth and degrees of difficulty, so detailed and careful planning is prerequisite.

Figure 8. Drilling scheme

THE SCIENCE PLAN—PREAMBLE

Maarten de Wit Africa Earth Observatory Network, Nelson Mandela Metropolitan University, Port Elizabeth, South Africa

Earth processes proceed at variable speeds, from steady and slow, to fast, sometimes showing gradual change, sometimes sudden, and sometimes impinging catastrophically on ecosystems. In rock systems these changes are recorded as stratigraphical interference patterns that geoscientists convert with ever-greater precision into a narrative full of complexity and surprises. We do not fully comprehend the system (Ager, 1973; Rudwick, 2005; Blackburn et al., 2013), but progress has been made: *geoscience* has self-organised into *earth systems science* enabling more complex questions to be addressed about systemic interdependencies and connectivity of palaeo-processes; about how oceans that opened and closed affected palaeo-global currents, climates, weathering, seawater chemistry, and biodiversity. And when it became clear that such hyperconnectivity is vulnerable to failure through rapid external forces, such as extraterrestrial impacts or large mantle plumes, *earth systems science* suddenly stumbled into a new era of exploring Earth as a complex interactive adaptive system.

Fundamental insights into how the Earth functions as a complex autocatalytic and adaptive system emerged at the end of the 20th and early in the 21st century, following exciting evidence, for example, of the co-evolution of Earth and life systems: the connectivity between black smokers and ecosystems; or that of global changes emerging out of the atmospheric 'symphony' of fluctuating palaeotemperatures and palaeo-gas concentrations, as recorded in ice cores. These, and similar discoveries forced a relatively rapid irreversible shift in focus from closed-system solid-Earth geodynamics to its syngeosis with the external gas–fluid envelope, the exosphere. The solid Earth's 'leaky' systems, each evolve whilst interacting with each other, recycling through non-linear, positive and negative, slow and fast, feedback reactions forced by seemingly unpredictable fluctuations in energy and mass exchange. But, this ubiquitous connectivity is poorly understood.

Complex systems are comprised of many interactive parts with the ability to generate a new quality of collective behaviour through self-organisation (Prigogine, 1984; Odem, 1988; Bak, 1996; Camazine et al., 2001; Ben-Jacobs, 2002). Petrologists have long documented evolving patterns and phase changes (solid–liquid–gas as a function of pressure, temperature and composition) in mineral and rock systems at the edge of chaos (fluids). At such special phase boundaries self-organisation is spontaneously constituted, and further complexity evolves through dissipative processes. Scale-invariant earth sys-

Unearthing palaeo-complexity through continental scientific drilling for the benefit of future generations.

Figure 9. Complexity word cloud

tems somehow all appear to acquire the ability to hover between order and chaos. Ongoing ICDP projects which are looking into the supercritical zones of hydrothermal and magmatic complexes are already providing new and needy observational data to test for conditions of instability at mantle scales. Similarly, fast response drilling into fault zones can test for critical states in the crust.

Self-organisation in natural systems emerges from a dynamic hierarchy of information. Self-organisation of earth systems reconnects its parts and processes into new operating cycles through evolving information between core, mantle, crust, air, oceans, and life. No model can yet account holistically for such dynamic connectivity within natural information systems (Toniazzo et al., 2005). Some argue that the basis for this is simply rooted in the second law of thermodynamics to maximise entropy production unbeholding to cause and effect. Systems dissipate and reorganise, driven by simultaneous interactivity far from equilibrium (Kleidon and Lorenz, 2005). Others entertain the view that the entire planet is a self-organising system that maintains homeostasis through cause and effect (Lovelock, 1972). Which system dominates the Earth is still open to debate, but can be tested with new high-resolution data and disruptive thinking.

Increasingly, ecosystem studies have generated concepts that may apply to all complex systems when appropriately generalised with network models, energy, and information. High-fidelity stratigraphical studies may recognise such signals in geosystems too. The ICDP community and their IODP colleagues have unique opportunities to core disparate archives that overlap in time and space to search for palaeo-connectivity between earth systems, to reconstruct a palaeo-interconnected world, and tease-out local and global adaptive behaviour of the past. Bringing together the observations from time-overlapping cores retrieved from lakes, ice, speleothems, rocks and minerals, will lead to better understanding of palaeo-adaptive systems over deep time and add immense value to drilling projects.

The ability to compare overlapping sequences across the planet, at selected

Figure 10. Decadal map of ICDP drill sites (2004–2014) showing locations of completed, planned and proposed continental drilling projects, together with their projected archival time-spans. Numbers along the chronostratigraphical timescale are in millions of years; note that out of a 145 sites, 52% of planned cores overlap within the most recent 2.6 million years [Quaternary (P=Pleistocene; H=Holocene)]; whilst 4% overlap within the earliest 1500 million years of earth history for which there is a preserved rock record (modified from Soreghan and Cohen, 2013).

lines of longitude across the equator to the poles provides tests for global changes. It can provide estimates of the amplification of system sensitivity caused by positive feedbacks, to develop a general set of algorithmic approaches for quantifying the way complex adaptive systems interact with one another, and how they get connected through nature's incessant compulsion for self-organisation into evolving patterns. In deeper time too, overlapping sequences from ancient cratons will likely link high-fidelity fluctuations in biogeochemistry systems and early life.

Understanding how complex self-organising systems respond to external forcing is important, especially the emergence of feedbacks sometimes passing 'points of no return' without warning before approaching tipping points ('catastrophic bifurcations'). There are now signs that tipping points can be predicted when critical thresholds are approaching, spatially as well as temporally (Rietker et al., 2004; Scheffer et al., 2009; Carpenter et al., 2011; Carpenter, 2013; Dai et al., 2013).

With more deep-spatial and deep-time data it may become possible then to make more robust predictions about a future Earth to strengthen cohesion with socio-economic and political systems, and to develop a greater planetary culture to combat looming crisis (Morin and Kern, 1999; Hansen et al., 2013). New endeavours like *earth stewardship science* can collate the required critical knowledge to stimulate self-organised paradigm shifts in transdisciplinary thinking to bridge the gap between the earth and social-system sciences.

Today's strongly connected global process networks are highly interdependent systems that we do not understand well (Helbing, 2013). These systems are vulnerable to failure and can become unstable at all scales even when external shocks are absent. As the complexity of interactions in global networked palaeosystems becomes better understood, we may develop technologies to make the anthropogenic systems manageable so that fundamental redesign for future systems may become a reality.

We are at the threshold of new transdisciplinary thinking about earth system complexity, and there will be a long list of relevant questions that we must ask of the cores from drilling programmes. Inspection of the spatial and temporal distribution of ICDP's archived and anticipated drill-core (Figure 10) provides powerful argument for constructive engagement and efficient design of time-overlapping coring across the globe through collaborative drilling projects to chart the connectomics of our planet from core to space; and from the past into the future.

Acknowledgements

I have benefited greatly from 10 years interactive discourse on the ICDP Science Advisory Group, under the leadership of Stephen Hickman, who can create order out of any chaos. I am grateful to ICDP for their facilitating role and generous funding and to Bastien Linol for help with Figure 10.

References

Ager, D. V. 1973. The Nature of the Stratigraphical Record. Halsted (Wiley), New York, 114 pp. (3rd edition 1992; 151 pp.).

Bak, P. 1996. How Nature Works: The Science of Self-Organised Criticality, New York: Copernicus.

Ben-Jacobs, E. 2002. When order comes naturally. Nature, 415, 370.

Blackburn, T. J.,Olsen, P. E., Bowring, S. A., McLean, N. M., Kent, D. V., Puffer, J., McHone, G., Rasbury, E. T., Mohammed Et-Touhami, T. M. 2013. Zircon U-Pb Geochronology Links the End-Triassic Extinction with the Central Atlantic Magmatic Province. Science, 340, 941–945.

Camazine, S., Deneubourg, J-L., Franks, N. R., Sneyd, J., Theraulaz, G., Bonabeau, E. 2001. Self-Organisation in Biological Systems. Princeton University Press. 538 pp.

Carpenter, S. R. 2013. Spatial signatures of resilience. Nature 496, 308–309.

Carpenter, S. R., Cole, J. J., Pace, M. L., Batt, R., Brock, W. A., Cline, T., J. Coloso, J., Hodgson, J. R., Kitchell, J. F., Seekell, D. A., Smith, L., Weidel, B. 2011. Early Warnings of Regime Shifts: A Whole-Ecosystem Experiment. Science, 322, 1079–1082.

Dai, L., Korolev K. S., Gore, J. 2013. Slower recovery in space before collapse of connected populations. Nature 496, 355–358.

Hansen, J. (plus 17 coauthors). 2013. Assessing 'dangerous climate Change': Required Reduction of Carbon Emissions to Protect Young People, Future Generations and Nature. PLOS One 8, 12, 1–26.

Helbing, D. 2013.Globally networked risks and how to respond. Nature, 497, 51–59.

Kleidon, A., Lorenz, R. D. 2005. Non-equilibrium thermodynamics and the production of entropy. Springer-Verlag, Berlin. 260 pp.

Lovelock, J. E. 1972. Gaia as seen through the atmosphere. Atmospheric . Environment 6, 579–580.

Morin, E. and Kern, A. B. 1999. Homeland Earth: a Manifesto for the new Millenium. Advances in system theory, complexity and the human sciences. Hampton Press, Inc. NJ. 153 pp.

Odem, H. T. 1988. Self-Organisation, Transformity and Information. Science 242, 1132–1139.

Prigogine, I. 1984. Order out of Chaos. Toronto. Bantam Books.

Rietkerk, M., Dekker, S. C., de Ruiter, P. C., van de Koppel, J. 2004. Self-Organised Patchiness and Catastrophic Shifts in Ecosystems. Science 305, 1926–1929.

Rudwick, M. J. S. 2005. Bursting the Limits of Time —The reconstruction of Geohistory in the Age of Revolution. The University of Chicago Press, Chicago and London, 708 pp.

Scheffer, M., Bascompte, J., Brock, W. A., Brovkin, V., Carpenter, S. R., Dakos, V., Held, H., van Nes, E. H., Rietkerk, M., Sugihara, G. 2009. Early-warning signals for critical transitions. Nature, 461, 53–59.

Soreghan, G. S. and Cohen, A. S. 2013. Scientific drilling and the evolution of the earth system: climate, biota, biogeochemistry and extreme systems. Scientific Drilling, 16, 63–72.

Toniazzo, T., Lenton, T. M., Cox, P. M., Gregory, J. 2005. Entropy and Gaia: is there a link between MEP and Self-regulation in the climate system? In: Non-equilibrium thermodynamics and the production of Enthropy (eds. A Kleidon and R. D. Lorenz). Springer-Verlag, Berlin. p 223–241

PAVING THE WAY FORWARD—THE SCIENCE PLAN

ACTIVE FAULTS AND EARTHQUAKES

GLOBAL CYCLES EFFECTING CLIMATE AND ENVIRONMENTAL CHANGE

HEAT AND MASS TRANSFER

THE UBIQUITOUS HIDDEN BIOSPHERE

CATACLYSMIC EVENTS—IMPACT CRATERS AND PROCESSES

ACTIVE FAULTS AND EARTHQUAKES

Jim Mori Disaster Prevention Research Institute, Kyoto University, Kyoto, Japan
William Ellsworth U.S. Geological Survey, Menlo Park, USA

Figure 11. An automobile crushed under the third story of an apartment building in the Marina District, San Francisco. The Loma Prieta earthquake in 1989, magnitude 6,9.

Lay of the land

A single earthquake and associated tsunami in a populated region can kill tens of thousands of people and cause huge economic losses that are a significant percentage of the GDP of the stricken country. The developing countries (the 2010 M7.0 Haiti earthquake killed over 100,000 people) and technologically advanced countries (the M9.0 2011 Tohoku earthquake in Japan caused several hundred billion dollars of damage) are all prone to these disasters. A few research boreholes drilled into active faults and equipped with monitoring tools is not going to immediately reduce the damage from earthquakes; this takes time and is an ongoing endeavour. However, contributions to scientific knowledge, as described in the following sections, address critical issues such as establishing occurrence rates of severe events and evaluating the intensity of the damaging ground shaking. Also, drilling projects draw public attention to the seismic hazards of a region and can be the catalyst for effective education and outreach efforts.

Earth tremors and earthquakes can be induced; with the increasing production of shale gas and shale oil, the building of reservoirs for hydroelectricity, and the pumping of fluids into underground storage areas, it is clear that the last dec-

ade has seen a dramatic increase in the earthquakes associated with human activities (e.g. Gupta, 2002; Ellsworth, 2013). A better understanding of conditions and mechanisms of these seismic events should lead to better-informed policies for the regulation and operation of activities.

Past accomplishments in ICDP

During the last two decades, deep borehole drilling into fault zones has opened new fields of research for a better understanding of earthquake processes. Land-based drilling projects on the Nojma Fault Japan, (Ando et al., 2001), San Andreas Fault, USA (Zoback et al., 2011), Chelungpu Fault, Taiwan, (Ma et al., 2006), Wenchuan Earthquake Fault, (China, Li et al., 2012), Gulf of Corinth, Greece (Cornet et al., 2004), and Alpine Fault, New Zealand, (Toy et al., 2013a) along with ocean drilling in subduction zones of the Nankai Trough (Tobin et al., 2009), Japan Trench (Chester et al., 2013), and Costa Rica (Vannucchi et al., 2013), have obtained valuable samples from active fault zones from depths reaching several kilometres. We have obtained a much better knowledge of the physical properties of active fault zones that produce large damaging earthquakes. An important result is recognition of the immense complexity observed in the fault zone rocks, including their varied structural and chemical characteristics, along with the associated fluid properties (Figure 12).

We have begun to answer some of the key questions raised 20 years ago when the first boreholes into fault zones were being planned, and significant progress has been made in answering these questions.

- Why are major plate-boundary faults like the San Andreas Fault weak?
- How do stress orientations and magnitudes vary across the fault zone?
- What are the width and structure (geological and thermal) of the principal slip surface(s) at depth?
- What are the mineralogies, deformation mechanisms and frictional properties of the fault rocks?
- How is energy partitioned within the fault zone between seismic radiation, frictional heating, comminution and other processes?

Fundamental open questions

In the next decade, future fault zone projects will continue to improve our understanding of the structure and processes of active faults which result in large earthquakes, by focusing on these issues:

- How do earthquakes nucleate?
- How do they propagate?
- Why do they stop?
- What controls the levels of ground motion during earthquakes?
- What controls the frequency and size of earthquakes
- How does fault permeability and fluid pressure vary during earthquakes?
- How does stress magnitude and orientation vary during the earthquake cycle?

Future scientific targets

From discussion at the 2013 ICDP Science Meeting, we have identified

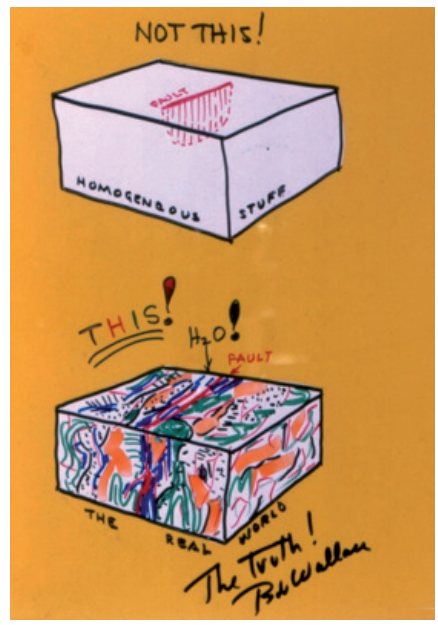


Figure 12. The complexity of real fault zones.

research areas that can be advanced through drilling projects and have the potential for producing critical new results for understanding earthquakes.

Induced earthquakes

It has been recently recognised that an increasing number of earthquakes are associated with human activities such as reservoir filling, mining, waste-water injections, and CO_2 sequestration. Induced earthquakes of small to moderate size have caused damage throughout the world (e.g. 1967 Koyna, India; 2011 Oklahoma; 2006 Basel, Switzerland). In many of the documented cases in the literature, variations in pore fluid pressure are implicated as the primary physical mechanism that triggers earthquakes (e.g. Gupta, 2002; Deichmann and Giardini, 2009; Ellsworth, 2013). Major questions remain about how fluid pressure migrates through the Earth, and how ancient faults can be reactivated by this mechanism. Resolution of these and other questions requires in-situ observations in boreholes in the source regions of these earthquakes. ICDP can play an important role in investigating the physical and chemical processes and evaluating hazard implications of such human-induced seismic events.

Role of fluids

The importance of the effects of water for both natural and induced earthquakes has long been appreciated. However there is currently only limited information about the permeability structure of fault zones, flow paths of fluids and the role chemical reactions of introduced waters play in modifying the permeability structure. Permeabilities can vary by orders of magnitude across varying geological structures and have a strong effect on the frictional properties of the fault during large earthquakes (e.g. Tanikawa et al., 2013). Borehole studies of the fluid-flow and pressure transmission regimes may thus produce important results.

Borehole observatories

The last decade has seen a rapid increase in the development and installation of borehole instrumentation on the San Andreas Fault (Zoback et al., 2011), Chelungpu Fault (Ma et al., 2012), North Anatolian Fault (Bohnhoff, 2013), and at various other locations around the world (Figure 16). These instruments record a variety of types of data such as seismic waves, deformation and tilt, temperature, and fluid pressure. Boreholes provide unique access into the nearfield region of the earthquake source and provide extremely low noise conditions for observing the system, which is not attainable at the Earth's surface. ICDP can play an important role in coordination of instrument development among different groups and support for deployment at important sites on active seismic regions.

For example, little is known about the source mechanisms of low-frequency earthquakes that may occur in more ductile regions of the crust. Borehole observations of these and other types of seismic and deformation events can lead to a better understanding of the wide range of physical mechanisms for strain accumulation and release in the crust.

Figure 13. Start of drilling at the GONAF location in Tuzla, Turkey

DOWNHOLE EARTH OBSERVATORY

Marco Bohnhoff, Georg Dresen GFZ—German Research Centre for Geosciences, Germany

High-resolution downhole seismic monitoring

In order to perform high-resolution seismic monitoring of critical faults overdue to generate large earthquakes, it is necessary to place geophones in low-noise environments and as close as possible to the fault zone. Such conditions can be met only by drilling boreholes located close to the target fault. Beginning in the late 80s in the USA and Japan, borehole installations have been successfully operated throughout the last decades. Much experience has been gained from these efforts, in particular from the local high-resolution seismic network (HRSN) on the San Andreas Fault in California and the Hi-net in Japan. Such installations are still rare but have produced unique earthquake waveform recordings, providing state-of-the-art seismological research for decades, demonstrating that the effort needed for implementing permanent downhole monitoring systems pays off on the long term.

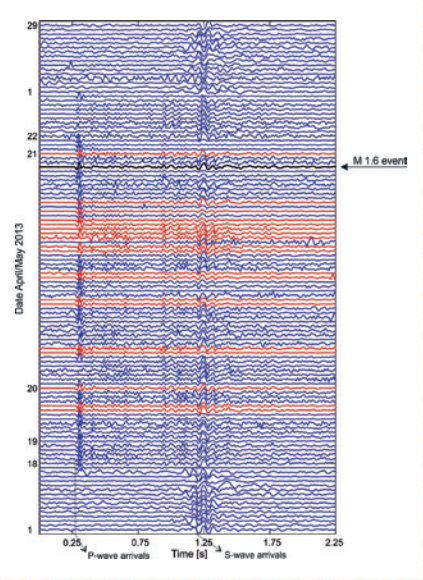


Figure 14. Recordings of the Tuzla earthquake swarm of 2013

The ICDP-GONAF project

The North Anatolian Fault Zone in Turkey has produced several large (M>7) earthquakes in the historic past leaving the Marmara Sea segment as the only part of the entire fault zone that has not generated a major earthquake since 1766. Currently, there is a high probability for a major earthquake less than 20 km from the roughly 13 million people who live in Istanbul. In order to monitor this critical part of the fault, a borehole Geophysical Observatory at the North Anatolian Fault zone (ICDP-GONAF project) has been initiated. GONAF is a joint research venture between GFZ Potsdam and the Turkish Disaster and Emergency Presidency (AFAD) in Ankara. When completed, it will comprise an eight-station earthquake downhole observatory, each equipped with vertical arrays of seismometers in 300 m deep boreholes on the mainland and on the Princes Islands being located within 3 km to the fault.

Key challenges

The principal objectives of the GONAF project are to monitor microseismic activity and deformation processes in the broader Istanbul region using downhole seismic observations over the entire seismic frequency band as well as GPS and strain meter measurements. Microseismicity will be monitored at low magnitude-detection threshold and with high precision not achievable with surface recordings. Using the downhole observations, the driving physical processes along a transform fault segment, which is in the final state of its seismic cycle, will be studied prior, dur-ing and after a large (M 7+) earthquake. Furthermore, the role of structural heterogeneities of the NAFZ below the Sea of Marmara will be investigated for slip distribution, nucleation process, and magnitude of the pending Marmara earthquake.

Drilling holes is more than just collecting samples. Installation of sensitive instruments in boreholes allows us to directly access the underground where earthquakes nucleate. This is the key for near-source earthquake monitoring providing the base for improved seismic risk and also resource management.

Experiments on core material and modeling

Laboratory analysis of rock, fluid and gas samples from active faults obtained from depth provide important information on the physical and chemical properties of fault deformation mechanisms. These mechanisms span the range from continuous creep to sudden slip in earthquakes (e.g. Ikari, 2013). The rate dependence of friction and temporal evolution of fault-zone permeability are just two of the important parametres that can only be obtained from direct sampling of faults in-situ. Understanding of the physical and chemical processes that lead to the development of the fault core where the great majority of the sliding occurs and surrounding damage zone requires the retrieval of a broad suite of samples of fault rocks and fluids. Such physical data is especially needed to constrain dynamic modeling of earthquake ruptures (Avouac et al., 2013)

In-situ experiments

To bridge the gap between simulated earthquakes in the laboratory (millimetre to metre scale) and the kilometre dimensions of natural earthquakes, we need better knowledge about the behavior of materials for in-situ conditions. Experiments at depth in real fault zones can study the conditions for producing earthquakes using small displacements of the actual rock masses under natural stress and temperature conditions (e.g. Henry et al., 2013).

Deep mines also provide a natural laboratory for studying failure mechanisms. They provide straightforward access to the locus of deformation induced by mining and can be extensively instrumented with seismic and deformation instrumentation in the extreme near-field of the process, such as in the South African goldmines (e.g. Ogasawara et al., 2013).

Another potential experiment uses injection of water into a fault zone to produce small earthquakes. An experiment of this type was done at Rangely, Colorado, USA more than 40 years ago when an array of boreholes into a fault zone were used to modulate the rate of earthquakes (Raleigh et al., 1976). This experiment verified the effective stress mechanism for triggering earthquakes by modulating the pore fluid pressure inside the fault. Today, critical questions remain about the feedback between fault movement and the enhancement of permeability within a fault as it moves in a series of small earthquakes, or the controls on the magnitude of earthquakes induced by this mechanism.

Geological records of tsunamis and earthquakes

Geologists are always seeking new methods for extending the record of past earthquakes and other large catastrophic events beyond the written historical record. Coastal deposits from large tsunamis (produced by earthquakes, volcanic events, meteorite impacts), as identified in borehole cores, can be used to gain a better knowledge of such events. Giant M earthquakes, such as the recent 2004 Sumatra, Indonesia and 2011 Tohoku, Japan earthquakes produced global-scale tsunamis which can be studied using coastal

Figure 15. Affected dam after the Jiji earthquake in 1999, Taiwan

Figure 16. Locations of continental fault-zone drilling projects, borehole observatories and in-situ experiments discussed in the Active Faults and Earthquake Processes session at the ICDP Science Conference.

boreholes (e.g. Fujiwara, 2013). Also records from regions that have very high sedimentation rates, such as glacial and lake deposits, can provide new opportunities for extending earthquake histories (Toy et al., 2013b).

Deep processes and tectonics

In addition to providing detailed fault-zone characterisations, observations made in boreholes provide the only direct means for measuring the state of stress in the Earth. Knowledge of the orientation and magnitude of the stress field and its spatial variability may hold the key to understanding the variability in earthquake rupture and seismic wave radiation, as well as providing important constraints on regional tectonic processes and deeper mantle processes.

Capture the complete earthquake cycle

Past drilling projects have investigated fault zones soon after the occurrence of a large earthquake (Chelungpu and Wenchuan), while others have studied physical characteristics of faults in various stages of the earthquake cycle. In the future, we envision a large-scale project to make detailed subsurface observations before, during and after a large earthquake. For such studies, it is essential to measure the physical state of the fault before the event and have in place a borehole that can rapidly be reoccupied to observe the rapid temporal evolution of the fault immediately after a large slip event. Clarifying time-dependent changes in the physical and chemical properties should lead to important new insights for understanding the whole process of earthquake occurrence.

Drilling issues

Reaching the depths of the seismogenic zone where earthquakes nucleate has always been a challenge for fault-zone drilling projects. The maximum depth reached in a fault-zone drilling project was 3.0 km at SAFOD, although, for comparison, exploratory oil and gas wells have been drilled to over three times this depth. For core sampling, there is the desire to reach greater depths and pressures which may be more representative of the overall fault conditions of a large earthquake. Obtaining fault zone cores from depths of 5 to 10 km will need new cost-effective techniques for deep drilling, including advanced techniques for better recovery of the fragile fault zone.

For borehole observatories, such as the GONAF array along the North Anatolian Fault in Turkey (Bohnhoff et al., 2013), more numerous sites with relatively shallow boreholes are needed to emplace seismometres, strainmetres and other instruments in competent rock at a depth of a few hundred metres. ICDP could lead efforts to develop efficient drilling and deployment strategies for such borehole installations.

Also, improved logging tools and new techniques for analysing cuttings are needed to optimise the information gained during the drilling.

Recommendations

1. Studying earthquakes using drilling provides unique opportunities for high-profile, high-scientific return investigations that hold the potential to revolutionise our understanding of active faulting and earthquake processes.

2. These questions are of high interest to the public, so appropriate education and outreach efforts should be considered from the planning stages. Furthermore, serious consideration should be given to the practical applications of the scientific results to seismic hazard evaluations and mitigation.

3. ICDP workshops should be introduced to discuss broader logistical and design issues common to all earthquake investigations, rather than just the development of specific drilling proposals. Possible topics that would be of interest to the scientific community include technologies in borehole observatories, applications for seismic hazard assessment, and a roadmap for a coordinated global fault zone drilling programme.

Figure 17. Two scientists holding a drill core that contains the Alpine Fault, New Zealand.

References

Ando, M., Geological and geophysical studies of the Nojima fault from drilling: An outline of the Nojima fault zone probe, Island Arc, 10, 206–214, doi:10.1111/j.1440-1738.2001.00349, 2001.

Avouac, J-P., S. Barbot, N. Cubas, N. Lapusta, Spatial variations of fault friction: Observations and implication for fault dynamics, ICDP Science Conference, Imaging the Past to Imagine Our Future, 2013.

Bohnhoff, M., G. Dresen, F. Bulut, C. Rabu, F. T. Kadirioglu, T. Kilic, R. Kartal, M. Nurlu, P. Malin, H. Ito, GONF: A borehole-based geophysical observatory at the North Anatolian fault zone in NW Turkey, ICDP Science Conference, Imaging the Past to Imagine Our Future, 2013.Chester, F. M., C. Rowe, K. Ujiie, J. Kirkpatrick, C. Regalla, F. Remitti, J. C. Moore, V. Toy, M. Wolfson-Schwehr, S. Bose, J. Kameda, J. J. Mori, E. E. Brodsky, N. Eguchi, S. Toczko, Expedition 343 and 343T Scientists, Structure and composition of the plate-boundary slip-zone for the 2011 Tohoku-oki earthquake, Science, 342, 1208–1211, doi: 10.1126/science.1243719, 2013.

Cornet, F. H., M. L. Doan, I. Moretti, G. Borm, Drilling through the active Aigion fault: The AIG10 well observatory, Compi. Rendus Geosci., 336, 395–406, 2004.

Deichmann, N., D. Giardini, Earthquakes induced by the stimulation of an enhanced geothermal system below Basel (Switzerland). Seismol. Res. Lett. 80, 784–798 doi: 10.1785/gssrl.80.5.784, 2009.

Ellsworth, W. L., Injection-Induced Earthquakes, Science, 341, doi: 10.1126/science.1225942, 2013.

Fujiwara, O., Geohazard (widespread catastrophic damage caused by mega tsunamis), ICDP Science Conference, Imaging the Past to Imagine Our Future, 2013.

Gupta, H. K., Review of recent studies of triggered earthquakes by artificial water reservoirs with special emphasis on earthquakes in Koyna, India, Earth-Science Reviews, 58, 279–310, 2002.

Henry, P., Y. Guglielmi, F. Cappa, Hydromechanical studies of the seismic source with the step-rate injections method for fracture in-situ properties (SIMFIP), ICDP Science Conference, Imaging the Past to Imagine Our Future, 2013.

Ikari, M., The mechanics of fault slip explored by laboratory experiments on drilling samples, ICDP Science Conference, Imaging the Past to Imagine Our Future, 2013.

Li, H., H. Wang., Z. Xu, J. Si, J. Pei, T. Li, Y. Huang, S-R. Song, L-W. Kuo, Z. Sun, M.-L. Chevalier, D. Liu, Characteristics of the fault-related rocks, fault zones and the principal slip zone in the Wenchuan Earthquake Fault Scientific Drilling Project Hole-1 (WFSD-1), Tectonophysics, 584, 23–42, doi:10.1016/j.tecto.2012.08.021 2012.

Ma, K. F, H. Tanaka, S.-R. Song, C.-Y.Wang, Ji.-H. Hung, Y.-B. Tsai, J. Mori, Y.-F. Song, E.-C. Yeh, W. Soh, H. Sone, L.-W. Kuo, H.-Y. Wu ,Slip zone and energetics of a large earthquake from the Taiwan Chelungpu-fault Drilling Project,Nature 444, 473–476, doi:10.1038/nature05253, 2006.

Ma, K. F., Y. Y. Lin, S. J. Lee, J. Mori, E. E. Brodsky, Isotropic events observed with a borehole array in the Chelungpu fault zone, Taiwan, Science, 337, 459–463, doi:10.1126/science.1222119, 2012.

Ogasawara, H., H. Kato, G. Hofmann, D. Roberts, P. Piper, T. Clements, Y. Yabe, K. Sakaguchi, In-situ stress measurements to constrain stress and strength near seismic faults in deep level South African gold mines, 6th Int. Symp. on In-Situ Rock Stress, 2013.

Raleigh, C. B., J. H. Healy, J. D. Bredehoeft, An experiment in earthquake control at Rangely, Colorado. Science 191, 1230–1237, 1976.

Tanikawa, W., T. Hirose, H. Mukoyoshi, O. Tadai, W. Lin, Fluid transport properties in sediments and their role in large slip near the surface of the plate boundary fauilt in the Japan Trench, Earth Planet. Sci. Lett., 382, 150–160, 2013.

Tobin, H., M. Kinoshita, J. Ashi, S. Lallemant, G. Kimura, E. Screaton, M. Kyaw, H. Masago, D. Curewitz, IODP Exp. 314/315/316 Scientific Party, NanTroSEIZE Stage 1 Expeditions 314, 315, and 316: First drilling programme of the Nankai Trough Seismogenic Zone Experiment, Scientific Drilling, 8, 4–17, doi:10.2204/iodp.sd.8.01.2009, 2009.

Toy, V., C. Boulton, R. Sutherland, J. Townend, Petrogenesis of Alpine Fault Zone rocks based on results of the first phase of the Alpine Fault Drilling Project (DFDP-1) at Gaunt Creek, South Westland, New Zealand, ICDP Science Conference, Imaging the Past to Imagine Our Future, 2013a.

Toy, V., C. M. Moy, J. Howarth, Linking glacial and lake sediment palaeoseismic records to fault zone properties on the southern Alpine fault, ICDP Science Conference, Imaging the Past to Imagine Our Future, 2013b.

Vannucchi, P., K. Ujiie, N. Stroncik, IODP Exp. 334 Scientific Party, Expedition 334: An investigation of the sedimentary record, fluid flow and state of stress on the top of the seismogenic zone of an erosive subduction margin, Scientific Drilling, 15, 23–30, doi:10.2204/iodp.sd.15.03.2013, 2013

Zoback, M., S. Hickman, W. Ellsworth, Scientific drilling into the San Andreas fault zone—An overview of SAFOD's first five years, Scientific Drilling, 11, 14–28, doi:10.2204/iodp.sd.11.02.2011, 2011.

GLOBAL CYCLES EFFECTING CLIMATE AND ENVIRONMENTAL CHANGE

Lynn Soreghan Conoco-Phillips School of Geology & Geophysics, University of Oklahoma, Norman, USA
Ralf Littke Institute of Geology and Geochemistry of Petroleum and Coal, RWTH Aachen University, Aachen, Germany

Figure 18. Windswept valleys in Northern Africa as seen from space

Lay of the land

The Earth's climate is presently changing rapidly, requiring expensive adaptation strategies in many parts of the world. There is therefore ample motivation for pursuing questions on climate and environmental change. Doing so requires us to establish the full dynamic range of climate history on the planet, at all timescales (seasonal to billions of years), across key climate transitions. We must also document linked life responses to both gradually changing climate and catastrophic (rapid) events such as those induced by meteorite impacts and large volcanic eruptions. Drilling to obtain climate records from the ocean and ice caps has helped define global records on how the Earth's climate system responds to elevated levels of atmospheric CO_2 and provide data on how ice sheets and sea levels respond to a warming climate. ICDP provides a key input to the understanding of the climate system by investigating regional patterns of precipitation, such as those associated with monsoons or El Niño, or regional changes in ocean circulation. The response of the continental climates as recorded in lakes and other sediments has permitted this approach by ICDP, which will become an increasingly important input to regional climate models.

Achim Brauer, Markus Schwab GFZ—German Research Centre for Geosciences, Germany

A central aspect of the palaeoclimate research concept is the assessment of regional responses to global changes and their variations in time as well as deciphering leads and lags between different regions.

Lakes can be viewed as a rain gauge for the climate of a region and in turn a sensitive recorder of the climate variability on continental regions. Since reconstructions of climate, environment and magnetic field changes from natural archives strongly relies on robust timescales, a key aspect of research is to establish precise chronologies based on annual sediment layers (varves) and tephrochronology.

For example, varved lake sediments from the Dead Sea basin drilled in the ICDP Dead Sea Deep Drilling Project DSDDP provide high-resolution records of climatic variability in the eastern Mediterranean region, which is considered, as is the entire Mediterranean region, to be especially sensitive to changing climatic conditions. The microfacies analyses of sediment cores, identification of biogenic components, analyses of the geochemical composition as well as the identification of former earthquakes in palaeoseismites enable the better understanding of past and future changes of climate and environment in this highly sensitive region (Migowski et al. 2004; Neugebauer et al. 2014). Results show that micro-facies analysis is a valuable tool to identify abrupt changes in sediments. This opens new perspectives for the identification of flood/erosion and dust deposition events in the 450 m long sediment record from the deep Dead Sea basin, which comprises the last two glacial–interglacial cycles (approximately 220,000 years) (Waldmann et al. 2010; Neugebauer et al. 2014).

In order to meet the research targets, geoscientists develop novel climate proxies based on the composition and structure of finely-layered lake deposits. The aim is the integration of long climate time-series from geo-archives and instrumental data to evaluate current changes in a comprehensive long-term context.

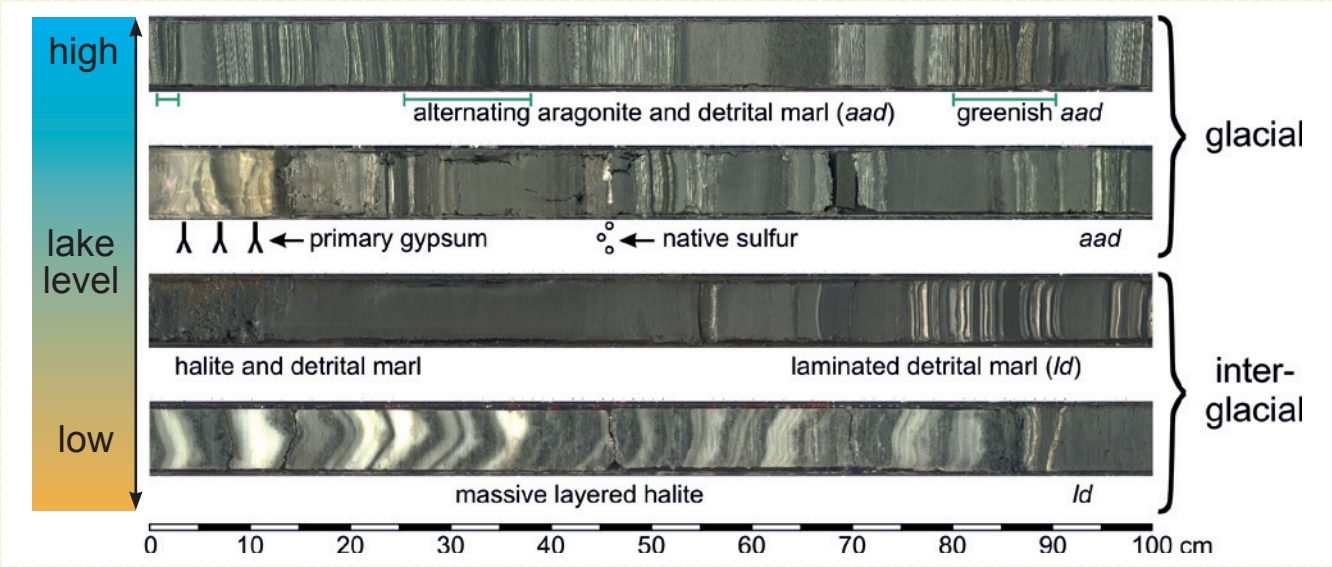


Figure 19. Exemplary identification of the sedimentary facies and paleoclimatic interpretation (lake levels) on core images of the ICDP Dead Sea DSDDP core 5017-1. Glacial times characterised by higher lake levels in the Dead Sea basin. Interglacial times characterised by lower lake levels.

Figure 20. Drilling campaign at Lake Czechowskie, Poland

A major challenge is the integration of information derived from different chemical, biological and physical proxies and sample types into a coherent picture. For example changes in climate are recorded in changes in ecosystems, mass wasting, and sea level, all of which have interlinked feedback mechanisms. It is in the integration of information that ICDP shares strong links with IODP and ice-coring programmes.

We are part of Earth's biosphere, and have become a major agent of change. Yet our ability to effect change on a planetary scale has rapidly outstripped our ability to grasp the implications of global environmental change. It is necessary to understand evolutionary history at a new level, using new approaches in some cases uniquely enabled by acquisition of core data, in order to understand life response to environmental perturbations. We need to establish the nature and scope of earth and environmental change in response to drivers, such as climate, in order to provide the boundary conditions for engineers and policymakers working to mitigate impacts and hazards. The earth system responds to changing climate in complex ways far beyond changing weather.

Past accomplishments in ICDP

A large portion of proposals to ICDP from its beginning focused on palaeoenvironmental research mainly addressing recovery of younger Quaternary sediments from large and mid-size lakes. Lake Baikal was drilled from a frozen-in barge during the Siberian winter and for the first time allowed continuous core recovery from a large lake. The data gained from these samples confirmed the great potential to record datable, continuous climate and environmental signals over long periods (Williams et al.). Several other lakes around the globe promised valuable palaeoclimate records from short piston cores. However, there was no deep

drilling tool available to be deployed on other lakes at affordable costs. Therefore ICDP, DOSECC and the US National Science Foundation sponsored workshops and finally the design and construction of the GLAD800 (Global Lake Drilling to 800 m). This was operated by DOSECC and successfully tested on Salt Lake and Bear Lake in Utah, Western USA (Colman et al., 2006). This progress paved the road to core recovery in mid to low latitude lacustrine basins including Lake Titicaca (Fritz et al., 2007), Lake Bosumtwi (Brooks et al., 2005), Lake Qinghai (Colman et al., 2007), Lake Malawi (Brown et al., 2006) and Lake Peten Itza (Hodell et al., 2006).

Regional climate variations, such as the change of the annual path of the Innertropical Convergence Zone during the last glacial cycles or continent-wide mega-droughts in Africa, shed new light on the climate evolution in the young Quaternary. Drilling at Lake Potrok Aike (Zolitschka et al., 2013) and Lake El'gygytgyn (Melles et al., 2012; Brigham-Grette et al., 2013) explored plaeoclimate in the high latitudes. The 3.6 million years continuous sedimentation in the Northeast Siberian, arctic Lake El'gygytgyn allowed study of the onset of the northern hemisphere glaciation as well as periods of warm 'super interglacials' which are related in time to the retreat of the West Antarctic Ice sheet implying strong interhemispheric climate connectivity.

Deeper lakes in the Eastern Mediterranean required the replacement of the GLAD800 by the Deep Lake Drilling System (DLDS) that was built and operated by DOSECC and transferred to ICDP ownership in 2014. It served to recover samples from Lake Van in eastern Turkey, from the Dead Sea, and from Lake Ohrid in Macedonia and Albania reaching through almost 300 m deep waters up to 550 m into the lacustrine strata. The Lake Van (Litt et al., 2012), Dead Sea (Stein et al., 2013) and Lake Ohrid (Wagner et al., 2014) sediments provided high-resolution insight in to the interplay of the Mediterranean to Middle East climate drivers reaching at least one million years of environmental history in the area. Collectively, lacustrine basin drilling and its use as a universal geological archive serve to add scientific value through integration of multiple ICDP projects.

Mesozoic strata in the southwestern USA of the Colorado Plateau comprise Triassic (252–202 Ma) sequences containing the first modern-style, rich land biota, and displaying a high resolution palaeoenvironmental terrestrial record bordered by major mass-extinction events. This succession served to address major issues of early Mesozoic biotic and environmental change (Geissman et al. 2014 in press).

The Precambrian era during which life, modern day tectonics, the growth of continents and the evolution of an oxygen-rich atmosphere began, has attracted ICDP research as well. The FAR-DEEP (Fennoscandian Arctic Russia—Drilling Early Earth Project) project documented the 500 Ma of Palaeoproterozoic evolution of sulphur, phosphorus, oxygen, carbon cycles that established the modern day ocean, atmosphere and

continental interaction (Melezhik et al. 2012). Another important time slice further back in time in the Archaean was sampled by the Barberton Drilling Project. In the Barberton Greenstone Belt supracrustal sedimentary and volcanic rocks formed 3.5 to 3.2 billion years ago and preserved the first surface on Earth and earliest evolution of life (Heubeck et al. 2013).

Fundamental open questions

In the next decade, palaeoclimate-related projects will continue to improve our understanding of the natural and anthropogenic influences on evolving Earth climate by focusing on questions such as:

- How did theEarth's climate system behave during warmer/high-CO_2 worlds?
- How did the Earth's climate system behave during glacial cycling in cold worlds, and during icehouse–greenhouse transitions?
- What are the fundamental processes and feedbacks forcing climate transitions, at timescales from decadal to million year and beyond?
- How fast did permafrost and gas hydrate stability react on changing climate and vice versa?
- What were the biotic responses to major environmental changes (e.g., climatic, super-eruptions, impacts), at timescales from decadal to million-year and beyond?
- How did oxygenation of the atmosphere evolve?
- What are the key processes characterising Earth's Critical Zone?

Future scientific targets

Lacustrine records, including additional Quaternary records

Long-lived lakes provide a rich, high-resolution continental record of near-time climate, and many 'benchmark' records of Quaternary climate are thus records from such lakes (e.g. Cohen, 2011). Future records to augment our understanding of the Plio-Pleistocene will continue to be found in long-lived lacustrine successions, including relatively deep-water targets. A distinct advantage to continuing to exploit this archive is the near-term capability of integrating these records globally in order to build datasets that can inform climate models at high spatial and temporal resolution. Such high-resolution, but globally distributed data-model comparisons would enable probing of key questions such as those related to Earth's climate and linked biotic behaviour during glacial cycling. For example, investigations of abrupt climatic/biogeochemical events at decadal to millennial timescales, and how are these propagated through the atmosphere–hydrosphere–biosphere systems? High-resolution, near-time targets are also needed to fully probe questions regarding the sensitivity of land surface processes to anthropogenic perturbations. Finally, lakes can enable a vastly improved understanding of phylogenies through the combined study of body and molecular fossil information in such self-contained ecosystems.

Drilling to access Earth's deep-time climate and biotic record

Clarifying our understanding of the full range of climate behaviour on the continents must involve expanding drilling targets to Earth's 'deep-time' (loosely, pre-Quaternary) record. Several key questions related to our understanding of Earth's climate system, driven largely by our current trajectory into a pre-Pliocene atmospheric composition, mandate the targeting of the deep-time record. As the Earth warms, for example, what can we learn from past warm intervals to inform our predictions of future behaviour? Furthermore, how can climate behaviour during both 'greenhouse' and 'icehouse' intervals of earth history inform understanding of various forcings—greenhouse gases, aerosols, solar, and tectonic—at various timescales. Critical, but poorly understood, processes include those related to

1) the regional and global behaviors of ice sheets, permafrost, gas hydrates and hydrology in warmer worlds
2) how abrupt climatic/biogeochemical events are triggered and propagated
3) what the biophysical feedbacks that either maintain equilibrium climate or trigger shifts to new states are.

Equally important as informing our understanding of climate is linking climate and environmental shifts to the evolution of life and ecosystems, at all timescales. This will involve new efforts aimed at reconstructing evolutionary history by integrating phylogenetic information with environmental records, and using cores to understand evolutionary events from body fossil records for example.

Drilling to access the Earth's earliest palaeoenvironmental and palaeobiological records

ICDP provides scientific records that extend to the origins of the preserved crust on Earth—over four billion years. Indeed some projects have focused on obtaining continental records of past geoprocesses related to the origin of life, the oxidation of the atmosphere, and the appearance of animals on land. Ocean records (IODP) through decades of drilling have provided an excellent record of the Earth in the Cenozoic (approximately the last 60 million years) and a scientifically interesting, but less well-developed records from the Jurassic to the Cenozoic (about 180 to 60 million years). Ocean records, however, do not extend to the pre-Jurassic, necessitating a focus on continental records for this vast majority of earth history.

Understanding the links between environmental change and life requires linking ecosystem change to records of evolution and extinction. This in turn requires data calibrated to a high-resolution geochronology, and continuous stratigraphical records with unambiguous superposition—a great benefit of core data. Core data also confers the benefit of access to unaltered material, increasingly critical for conducting organic and inorganic geochemical analyses (e.g. biomarker analysis, analysis of redox-sensitive elements; isotopes) so necessary for advanced investigations of the evolution of the biosphere.

Drilling to access the 'critical zone'

The 'critical zone' refers to Earth's outermost surface, from the vegetation cano-

py to the zone of groundwater (Brantley et al., 2006), and thus encompasses the nexus amongst the earth systems. Most terrestrial life resides in the critical zone, and it is rapidly undergoing transformation by anthropogenic changes. The critical zone is, indeed, the key record of the emerging Anthropocene. Drilling the critical zone will enable us to address, in an entirely new way, processes critical to sustaining life and driving evolution, such as weathering and nutrient cycling, and the biogeochemical cycling of carbon and other elements.

Permafrost and gas hydrates

Approximately 25% of the terrestrial surface of the Earth is associated with permafrost extending from the surface up to 1600 m depth. Relict permafrost formed, due to lower sea level during glacial periods, also exists on the continental shelves of the Arctic Ocean at water depths down to about 80 m. Depending on the geological history of the permafrost region, gas hydrates may occur below or within the permafrost layers and some of them are associated with conventional oil and gas reservoirs. Thawing of permafrost due to global warming may not only cause serious problems regarding the infrastructure and ecosystem in Arctic areas but also a temperature increase in permafrost regions that will result in a degradation of permafrost possibly inducing a decomposition of gas hydrates reservoirs. Depending on the local conditions the released methane from dissociated hydrates may migrate to shallower layers. In particular methane, released from hydrate reservoirs occurring under submarine permafrost on the shallow shelf, may migrate through the thawing permafrost and the shallow water and be released into the atmosphere. In addition, Arctic warming will result in an increase of lakes in area and depth on the coastal lowlands and form pathways of methane from decomposed gas hydrates to the surface and the atmosphere. Although such an increase in regional methane emissions might have serious impact on the global climate, very little is known about the potential decomposition of gas hydrates due to permafrost thawing and the resulting methane fluxes in terrestrial or in marine environments.

Data from long-term drilling projects in different permafrost regions monitoring the response of hydrate-bearing formations to global warming effects are necessary to verify or falsify the results of numerical models.

Figure 21. Core containing gas hydrates, Mallik project, Canada.

Drilling issues

New successes in understanding the Earth's global cycles in climate, life, and geodynamics requires advances in coring technology. Palaeoclimate studies require both continued acquisition of long cores in deep lakes, to acquire benchmark Plio-Pleistocene records, and acquisition of deep-time records to probe the full dynamic range of the climate system. This sampling in turn necessitates technical advances in drilling, e.g. the ability to recover core from deep water, moving ice shelves and challenging material such as unconsolidated sediment, and the ability to retrieve information from uncontaminated, unweathered reactive organic (includ-

ing DNA) and geochemical proxies of various geological ages. This goal will also benefit studies of biotic change at all timescales, including oxygenation in the deep-time record. Because long records of sedimentary rocks deep in sedimentary basins are available at petroleum companies, scientific cooperation is highly desirable.

In order to understand climate change, multi-proxy approaches will be needed including new proxies and new methods such as cosmogenic nuclides. For palaeomagnetic applications oriented cores are required. Additionally, implementation of horizontal drilling will enable collection of large volumes of event beds and fossil-rich horizons to benefit life studies. For drilling gas hydrates, preservation of in-situ pressures might be necessary. Geodynamic research will require the ability to drill to great depth, and potentially drill into magma chambers, for gas sampling. Most fundamentally, new discoveries in the operation of the Earth's global cycles will require the integration of data acquisition by coring with numerical modelling. This is especially critical for investigations into the climate system—at all temporal and spatial scales—as integration of data collection with climate modelling will ultimately push the envelope of our understanding, and thus capabilities for prediction. Finally, efforts on all fronts will be enhanced greatly by partnering with other organisations, including IODP.

Recommendations

1. Well-preserved geological records representing rapid climatic and environmental changes provide excellent opportunities to understand earth system dynamics at different timescales, especially if biotic response (on a body and molecular level) can be investigated.

2. Lake drilling, especially Holocene, should be coupled with numerical modelling and take IODP results into account, because a large dataset is already available for this period.

3. The excellent results of past ICDP sedimentary drilling operations should lead to a roadmap, based on a new critical integration of those results, for future drilling at world-class sites.

References

Brantley, S. L., White, T. S., White, A. F., Sparks, D., Richter, D., Pregitzer, K., Derry, L., Chorover, J., Chadwick, O., April, R., Anderson, S., Amundson, R., 2006, Frontiers in Exploration of the Critical Zone: Report of a workshop sponsored by the National Science Foundation (NSF), October 24–26, 2005, Newark, DE, 30 p.

Brigham-Grette, J., Melles, M., Minyuk, P. S., Andreev, A. A., Tarasov, P. E., DeConto, R. M., Koenig, S., Nowaczyk, N. R., Wennrich, V., Rosén, P., Haltia-Hovi, E., Cook, T. L., Gebhardt, C., Meyer-Jacob, C., Snyder, J., Herzschuh, U. 2013. Pliocene Warmth, Polar Amplification, and Stepped Pleistocene Cooling Recorded in NE Arctic Russia, 2013, Science 340, 1421 (2013); DOI: 10.1126/science.1233137

Brooks, K., Scholz, C. A., King, J. W., Peck, J., Overpeck, J. T., Russell, J. M., Amoako, P. Y. O. (2005): Late-Quaternary lowstands of lake Bosumtwi, Ghana: evidence from high-resolution seismic-reflection and sediment-core data. Palaeogeography, Palaeoclimatology, Palaeoecology, 216(3–4):235–249.

Cohen, A. S.: Scientific drilling and evolution in ancient lakes: Lessons learned and recommendations for the future, Hydrobiologia, 682, 3–25, doi:10.1007/

Colman SM, Kaufman DS, Bright J, Heil C, King JW, Dean WE, Rosenbaum JR, Forester RM, Bischoff JL, Perkins M, McGeehin JP (2006) Age models for a continuous 250-kyr Quaternary lacustrine record from Bear Lake, Utah-Idaho. Quaternary Science Reviews 25: 2271–2282

Colman, S. M., Yu, S.-Y., An, Z., Shen, J., and Henderson, A. C. G., 2007, Late-Cenozoic climate changes in China's western interior: A review of research on Lake Qinghai and comparison with other records: Quaternary Science Reviews, v. 26, p. 2281–2300.

Fritz, S. C., P. A. Baker, G. O. Seltzer, A. Ballantyne, P. Tapia, H. Cheng, and R. L. Edwards, 2007, Quaternary glaciation and hydrological variation in the South American tropics as reconstructed from the Lake Titicaca drilling project. Quaternary Research 68(3): 410–420.

Geissman et al. 2014

Giustiniani, M., Tinivella, U., Gas hydrate stability zone in shallow artic sea in presence of subsea permafrost, Proceedings oft he 8th International Conference on Gas Hydrates, Beijing, 2014.

Heubeck, Ch.; Engelhardt, J.; Byerly, G. R.; Zeh, A.; Sell, B.; Luber, T.; Lowe, D. R. (2013): Timing of deposition and deformation of the Moodies Group (Barberton Greenstone Belt, South Africa): Very-high-resolution of Archaean surface processes., Precambrian Research 231, 236–262

Hodell, D.; Anselmetti, F.; Brenner, M.; Ariztegui, D. and the PISDP Science Party (2006): The Lake Petén Itzá Scientific Drilling Project., 10.2204/iodp.sd.3.02.2006, Scientific Drilling 3 25–29

Litt, T.; Anselmetti, F. S.; Baumgarten, H.;Beer, J.; Cagatay, N.; Cukur, D.; Damci, E.; Glombitza, C.; Haug, G.; Heumann, G.; Kallmeyer, J.; Kipfer, R.; Krastel, S.; Kwiecien, O.; Meydan, A. F.; Orcen, S.; Pickarski, N.; Randlett, M. E.; Schmincke, H.-U.; Schubert, C. J; Sturm, M.; Sumita, M.; Stockhecke, M.; Tomonaga, Y.; Vigliotti, L.; Wonik, T. and the PALEOVAN Scientific Team (2012): 500,000 Years of Environmental History in Eastern Anatolia: The PALEOVAN Drilling Project., 10.2204/iodp.sd.14.02.2012, Scientific Drilling 14, 18–29

Melezhik, V.; Prave, A. R.; Hanski, E. J.; Fallick, A. E.; Lepland, A.; Kump, L. R.; Strauss, H. (eds.) (2013) A: Reading the Archive of Earth's Oxygenation., Springer, ISBN 978-3-642-29681-9 1 490pp

Melezhik, V.; Prave, A. R.; Hanski, E. J.; Fallick, A. E.; Lepland, A.; Kump, L. R.; Strauss, H. (eds.) (2013) B: Reading the Archive of Earth's Oxygenation., Springer, ISBN 978-3-642-29658-1 2 556pp

Melezhik, V.; Prave, A. R.; Hanski, E. J.; Fallick, A. E.; Lepland, A.; Kump, L. R.; Strauss, H. (eds.) (2013) C: Reading the Archive of Earth's Oxygenation., Springer, ISBN 978-3-642-29669-7 3 506pp

Melles, M., Brigham-Grette, J., Minyuk, P. S., Nowaczyk, N. R., Wennrich, V., DeConto, R. M., Anderson, P. A., Andreev, A. A., Coletti, A., Cook, T. L., Haltia-Hovi, E., Kukkonen, M., Lozhkin, A. V., Rosén, P., Tarasov, P. E., Vogel, H., Wagner, B. (2012): 2.8 Million years of Arctic climate change from Lake El'gygytgyn, NE Russia. Science, 337(6092), 315–320. doi:10.1126/science.1222135

Migowski, C., Agnon, A., Bookman, R., Negendank, J. F. W., Stein, M. (2004): Recurrence pattern of Holocene earthquakes along the Dead Sea transform revealed by varve-counting and radiocarbon dating of lacustrine sediments. Earth and Planetary Science Letters, 222 (1), 301–314.

Neugebauer, I., Brauer, A., Schwab, M. J., Waldmann, N. D., Enzel, Y., Kitagawa, H., Torfstein, A., Frank, U., Dulski, P., Agnon, A., Ariztegui, D., Ben-Avraham, Z., Goldstein, S. L., Stein, M., DSDDP Scientific Party (2014): Lithology of the long sediment record recovered by the ICDP Dead Sea Deep Drilling Project (DSDDP).—Quaternary Science Reviews, 102, 149–165.

Scholz, C. A.; Cohen, A. S.; Johnson, T. C. (eds.) (2011): Southern hemisphere tropical climate over the past 145ka: Results of the Lake Malawi Scientific Drilling Project, East Africa., 10.1016/j.palaeo.2011.01.001 Palaeogeography, Palaeoclimatology, Palaeoecology 303 (1–2)

Stein, M.; Ben-Avraham, Z.; Goldstein, S.; Agnon, A.; Ariztegui, D.; Brauer, A.; Haug, G.; Ito, E.; Yasuda, Y. (2011): Deep Drilling at the Dead Sea., Scientific Drilling 11 46–47

Wagner, B.; Wilke, T.; Krastel, S.; Zanchetta, G.; Sulpizio, R.; Reicherter, K.; Leng, M. J.; Grazhdani, A.; Trajanovski, S.; Levkov, Z.; Reed, J.; Wonik, T. (2014): More Than One Million Years of History in Lake Ohrid Cores., Eos, Trans-actions, American Geophysical Union 95 (3) 25–26, DOI: 10.1002/2014EO030001

Waldmann, N., Torfstein, A., Stein, M. (2010). Northward intrusions of low- and mid-latitude storms across the Saharo-Arabian belt during past interglacials. Geology, 38, 567–570.

Willilams DF, Kuzmin, MI, Prokopenko; AA, Karabanov, EB; Khursevich, GK; Bezrukova, EV, 2001, The Lake Baikal drilling project in the context of a global lake drilling initiative, Quaternary International 01/2001; DOI: 10.1016/S1040-6182(01)00015-5

Zolitschka, B.; Anselmetti, F.; Ariztegui, D.; Corbella, H.; Francus, P.; Lücke, A.; Maidana, N.; Ohlendorf, C.; Schäbitz, F.; Wastegard, S. (2013): Environment and climate of the last 51,000 years—new insights from the Potrok Aike maar lake sediment archive drilling project (PASADO)., 10.1016/j.quascirev.2012.11.024. Quaternary Science Reviews

HEAT AND MASS TRANSFER

Ilmo T. Kukkonen Solid Earth Geophysics, University of Helsinki, Helsinki, Finland
Guðmundur Ómar Friðleifsson Hitaveita Suðurnesja Orka HF, Reykjanesbæ, Iceland

Figure 22. Balloon experiments at the Karymsky volcano, Kamchatka, Russia

Lay of the land

The Earth is a thermally driven planet. Transfer of heat and mass, i.e., magma, hot fluids, groundwater and sediment, as well as the silent conduction of heat in the subsurface, are the basic processes responsible for the physical and geological world we live in. The socioeconomic consequences of heat and mass transfer are present in all branches of human culture, either directly or indirectly. Heat and mass transfer resulted, early on in the Earth's history, in an internal differentiation and layering of the planet, which is expressed on the surface level in the plate tectonic process, with dramatic seismicity and volcanism localised at well-defined global zones. Whereas seismicity and volcanic activity are great threats to mankind, heat and mass transfer is also extremely useful and important for society, namely in concentrating metals and hydrocarbons into economic deposits—which are indispensable for our civilisation—as well as providing renewable geothermal energy resources. The quest for carbon-free sustainable energy is one of the challenges of the modern society, but geothermal sources of energy—both high and low temperature—are still to a large extent unexplored and underused. This can be attributed to technological challenges encountered in exploiting the extreme environments but also

to a lack of understanding of the related physics, rock architecture and processes. Renewable energy technologies need also basic and rare earth element (REE) metals in batteries, heat exchangers and other high technology products. Scientific drilling is at the cutting edge of research providing new discoveries and basic understanding of heat and mass transfer for the benefit of the society.

High enthalpy geothermal energy, deep formation fluids and volcanic risk—Volcanoes pose both risks and benefits for society. Perhaps the most dangerous volcanic environments are encountered in silicic volcanic systems, especially in large silicic calderas (e.g. the Campi Flegrei area in Italy) which may generate huge eruptions threatening the population and infrastructure in vast areas, and exceeding the mass and energy consequences of normal central-vent type volcanoes by several orders of magnitude (DeNatale et al., 2006). Building a better understanding of the restlessness of large silicic calderas is of utmost importance for society. On the other hand, the high temperatures attainable at shallow levels in all types of active volcanic and near-surface magmatic systems provide a unique challenge and opportunity for the research of energy resources in terms of:

- drilling technology
- logging tools for high temperature
- physical properties of reservoir rocks (especially thermal and hydraulic)
- solution of corrosion problems due to chemically aggressive formation fluids (Asanuma et al., 2012; Markússon and Hauksson, 2015; Friðleifsson et al., 2005, 2015).

ICDP has already made some significant inroads in understanding the transport of heat in volcanic complexes, notably in the drilling projects in volcanic systems in:

- Iceland (Elders et al., 2014)
- Campi Flegrei (DeNatale et al., 2011)
- the Unzen volcano, Japan (Nakada et al., 2005)
- the hot spot volcanoes of Hawaii (Chang et al., 2005; McConnell et al., 1998; Stolper et al., 2009) and Yellowstone, US (Shervais et al., 2013, Shervais and Evans, 2014).

In addition to underpinning the development of geothermal energy resources, exploratory drilling in volcanic systems supplies fundamental information on understanding magma supply and heat transfer, in particular at the interface of magma chambers and their host rocks which could, in certain areas, provide a sustainable energy source (Friðleifsson and Elders, 2005; Asanuma et al., 2012).

Low enthalpy energy exploitation and mass storage—Understanding deep aquifers and aquitards (areas of very low permeability) is fundamental in geo-engineering processes in the Earth's crust. We have relatively good models for fluid flow in the upper tens of metres of the crust, and reasonable models for the uppermost 1–2 kilometres. However, increasingly society will be engineering the upper several kilometres of the crust for geothermal energy, energy storage, carbon capture and storage (CCS), unconventional energy production, and waste sequestration. A thorough characterisation of fluid pathways and transport mecha-

Figure 23. Geothermal power plant at Kizildere, Turkey

nisms in the upper kilometres of the crust is thus fundamental to underpin resilient economic development of the Earth and protect freshwater in aquifers. ICDP research drilling and associated borehole observatories will be essential in this process. It could be argued that we need to learn much more about the critical zone interface of the human technology and culture with the hydrosphere, atmosphere and near subsurface. We should work better with environmental scientists in characterising this 'zone with which humans interact' and improve its subsurface characterisation and monitoring.

Mineral resources—The swelling population of the planet and increasing demand for commodities have already changed the profile of mineral exploration and national mineral security (Vidal et al., 2013). Companies are now looking to exploit extreme environments (which are presently less anthropogenically impacted), such as the deep oceans and polar regions, for new resources. Interest is also increasing in exploration of resources at deeper levels in the crust than traditionally exploited. At the same time consumers seek new commodities, meaning there is a demand for certain rare elements used in electronics, new vehicles, new types of catalysts and high-performance magnets. It is not the role of scientific research programmes to explore for, and discover, new resources. Nonetheless, the development of novel technologies in the realms of satellite imagery, geophysical sounding and geochemical indicators for geological assessment and discovery of big deposits, will be essential. Research supported by ICDP should have a role in ground-truthing some of these technologies.

Past accomplishments in ICDP

Heat and mass transfer has been studied in numerous earlier ICDP projects (e.g. Harms and Emmermann, 2007). These include the normal crustal conditions, permafrost areas, active volcanic areas (mid-oceanic ridges, hot spot volcanoes and subduction systems), and meteorite impact craters.

Crustal and mantle heat flow and radiogenic heat production inside the Earth—These are basic thermal parametres affecting the present internal thermal regime, thermal power (heat flow) and thermal evolution of the planet. We still have considerable uncertainties in the estimates of global thermal output (Pollack et al., 1993, Davies and Davies, 2005) and the total concentration of radiogenic heat-producing elements (Dye, 2012). One of the important accomplishments in heat-flow studies during the past thirty years is the discovery of vertical variation in heat flow and temperature gradient of the present continental crust, a result partly achieved in ICDP projects and previous super-deep and deep drillhole studies (Kremenetsky and Ovchinikov, 1986; Clauser et al., 1997; Kukkonen and Jõeleht, 2003, Kukkonen et al. 2011). The increase of heat-flow density in the uppermost 2 km seems to be rather the rule than an exception in the continental crust (e.g. Kukkonen and Jõeleht, 2003; Majorowicz and Šafanda, 2007; Majorowicz and Wybraniecz, 2010). The upper-

GEOTHERMAL ENERGY

Ernst Huenges GFZ—German Research Centre for Geosciences, Germany

Temperature in the Earth

Heat can be obtained from the Earth in various ways. Deeper sources from three kilometres and more can be used for large heating networks and power generation. Combinations are also possible.

Geothermal energy is classified as a renewable resource because the tapped heat from an active reservoir is continuously restored by natural heat production, conduction and convection from surrounding hotter regions.

Geothermal systems

The figure shows geothermal systems used in central Europe. Relatively widespread are near-surface geothermal sources. Heat pumps use surface and ground water from a depth of a few meters as a heat source for space heating in houses. Installations of this type require only a few degrees of temperature difference in order to yield sufficient heat. A second heat source is hot water from deeper within the Earth. Such hydrothermal systems can be found in areas with active volcanism, but also in non-volcanic regions. Today, most of the large geothermal power plants in the world use steam and hot water from volcanically active regions to generate electric power. Geothermal reservoirs available in non-volcanic areas are hot, either deep water-bearing systems (hydrothermal systems) or systems (petrothermal systems) without or with limited water. Hydrothermal systems are deep water-bearing layers (aquifers) with naturally sufficient hydraulic permeability.

Key challenges

Many of the hydrothermal und all petrothermal systems can be developed to an economic use by the so-called 'Engineered Geothermal Systems (EGS)' concept. EGS technologies represent the sum of the engineering measures that are required to exchange the heat and to optimise the exploitation of the reservoir. All necessary system components are available, but there is still potential for improvement in terms of reliability and efficiency. A huge research demand exists in this field to make geothermal energy utilisation feasible in most environments in an environmentally friendly, safe and responsible manner.

In this context, scientific drilling is significant because most of the technologies for the exploitation of deep geothermal energy reservoirs require at least two wells. A production well is needed to recover water with an appropriate temperature from the reservoir and an injection well to return the water into the underground. Scientific drilling contributes to develop responsible management strategies and technologies for a sustainable use of geothermal resources worldwide.

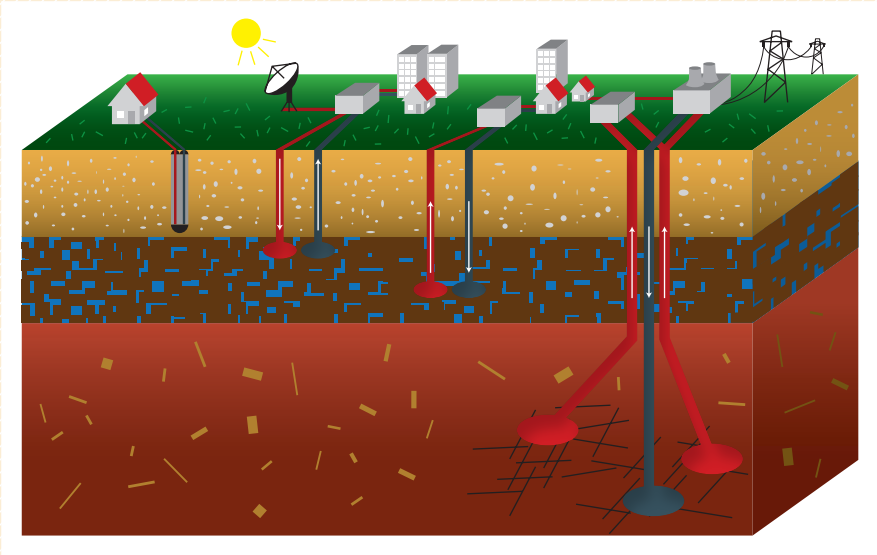


Figure 24: Illustration of energy resources utilized from Earth's underground.

most crust is in a thermally transient state and the variation can be mostly attributed to past climatic variations, especially the last glaciations 10,000 to 100,000 years ago (see e.g. Kukkonen et al., 2011, Šafanda et al., 2004) but the role of advective heat transfer may considerably affect the thermal regime in areas with significant hydraulic gradients and hydraulic permeabilities (Mottaghy et al., 2005). Therefore the depth to directly measure undisturbed heat flow densities usually exceeds 2 km. Such holes with reliable thermal data are relatively few in continents and almost absent in oceanic areas. The lack of reliable ground surface temperature histories at drilling sites mostly prevents simple forward calculation of the required palaeoclimatic corrections. In low heat flow continental areas the shallow level correction may amount up to several tens of percent of the steady-state value. On the other hand, where deep temperature profiles are available they can be inverted for the past ground surface temperature histories (Beltrami, 2002; Huang et al., 2000; Pollack and Smerdon, 2004). The above results challenge the representativity of data in existing heat flow databases and the average heat-flow values derived from such data, and thus, affect the estimates of global averages of thermal output of the planet. Heat-flow data from deep wells is continuously and globally needed.

High-temperature magmatic and hydrothermal systems—Mid-ocean ridges, subduction zones and hot-spot volcanoes host high-temperature magmatic and hydrothermal systems which are environments of crustal formation and mineral deposition as well as potential areas for very high enthalpy geothermal energy production. Due to the special properties of supercritical water, fluids above the critical point of water (> 374°C, > 22 MPa) are very interesting for energy production due to the expected improvement in energy production efficiency (Friðleifsson et al., 2014), though the technological challenges are huge for drilling and production in those conditions. Supercritical fluids are always at close proximity to magma which further complicates the drilling and in-situ studies. The ongoing *Iceland Deep Drilling* project has conducted pioneering research in such high-temperature conditions. The intention is to access fluid at supercritical conditions and bring it to the surface as superheated steam (400–600°C) at subcritical pressure (< 22 MPa). The IDDP-1 drill hole in the Krafla geothermal area was targeted to reach supercritical fluids but unexpectedly met molten (> 900°C) rhyolite magma at the depth of 2.1 km in 2009. After cooling the well bottom over a month and allowing it to heat again, the hole produced supercritical fluids (450°C / 4–14 MPa) for over two years during which time valuable experiments were undertaken (Hauksson et al., 2014). Supercritical dry steam containing volatile chloride may produce hydrochloric acid when cooled below dew point which results in strong corrosion of steel (Hjartarson et al., 2014) in turn making an additional challenge to energy production technology. However, the experiments done by Hauksson et al. (2014) showed that potential problems due to corrosion and scaling could be mitigated by simple chemi-

Figure 25. An ash-rich eruption plume rises from Sakura-jima above the city of Kagoshima, on July 19th, 2013. Sakura-jima is one of Japan's most active volcanoes and has been erupting almost continuously since 1955.

cal treatments (Markússon and Hauksson, 2015). The IDDP-1 experience from IDDP-1 at Krafla suggests that unintentionally the world's first Magma Enhanced Geothermal System (EGS) was developed and future prospect for economic benefits are very promising (Friðleifsson et al., 2015).

Active volcanic systems—Volcanism poses a significant threat to population, and understanding the volcanic processes and improving the predictions of the forthcoming eruptions is essential. Volcanism is driven by mantle-driven heat and mass transfer, and volcanic areas contain undeveloped resources for geothermal energy production. Drilling deep in active volcanic domes and calderas has rarely been done, but the ICDP-supported drilling projects have provided direct information on many volcanic areas, such as Unzen, Japan, Campi Flegrei, Italy, Snake River (Yellowstone), US, and Long Valley, US and Koolau, Hawaii, US (Chang et al., 2005; McConnell et al., 1998; Nakada et al., 2005).

The magma conduit of the *Unzen volcano* which had led to serious eruptions only a few years earlier was penetrated with directional drilling in an ICDP project in 1999 to 2004. The results indicated still high temperatures (< 200°C) and unexpectedly strong hydrothermal alteration in the magmatic dyke rocks in the conduit. It was the first time that in-situ observations were made in a recent and still-hot magma conduit (Nakada et al., 2005).

Campi Flegrei drilling project focuses on the famous caldera in southern Italy in an active volcanic area, which was formed by huge ignimbritic eruptions. Recent deformation of the caldera and uplift indicate increasing activity of the volcano. The location of the volcano next to the city of Naples includes a realistic risk for millions of people in a case of a serious eruption. The ongoing Campi Flegrei ICDP project has drilled a 500 m deep pilot hole, and the approcimately 2–3 km-deep oriented main hole is in preparation. Drilling will give fundamental, precise insight into the shallow substructure, the geometry and character of the geothermal systems and their role in the unrest episodes, as well as to explain magma chemistry and the mechanisms of magma–water interaction (DeNatale et al., 2011).

The project *HOTSPOT* drilled five holes in the Snake River Plain, Idaho, US, to track the Yellowstone Plume through space and time. The Yellowstone volcano has potential to produce huge eruptions in the continental scale, but how often such eruptions take place is uncertain. The Yellowstone and Snake River areas represent a world-class example of active mantle-plume volcanism in an intracontinental setting. The drill cores are expected to enlighten the problems of geochemical interaction of mantle-derived magmas with the continental lithosphere as well as formation of continental crust by magmatic underplating. The first results document significant, continuous bimodal magmatic flux long after the lithosphere has moved away from the hotspot. The downhole logging revealed a high

temperature aquifer at about 1.7 km depth indicating good potential for geothermal energy (Shervais et al., 2013, Shervais and Evans, 2014).

The *Hawaii Scientific Drilling Project* drilled core holes to a depth of 3.5 km in three phases between 1999 and 2007. Due to the moving Pacific Plate the Hawaiian volcanoes continuously 'sample' the deep mantle-plume-derived magmas. The geochemistry and isotopes of the intersected lava sequence of the Mauna Kea volcano revealed a smooth transition in the chemical and helium isotopic compositions from the central (alkaline basalt) to the exterior melt-producing zone (tholeitic basalt) of the plume. The bimodality and smooth variation is interpreted to represent radial variation in the deep mantle plume beneath Hawaii (Stolper et al., 2009). The age range of the lavas up to 680 kyr BP indicate that the lifetimes of the Hawaiian volcanoes are about four times longer than deduced from outcrop data. An unexpected deep circulation to a depth of about 1 km of cold sea water inward from the flanks of the volcano was revealed in temperature logs. This implied a more efficient cooling and alteration of the lava pile than previously anticipated and that the hydrogeology of oceanic volcanic islands is much more complicated than the traditional freshwater lens model of islands generally suggests (Thomas et al., 1996; Buettner and Huenges, 2002).

Fundamental open questions

Release of internal heat from the Earth by conduction through the crust is energy-wise the most important process in the continental crust, whereas the hydrothermal circulation in the young oceanic crust is the most important in marine areas (Lee and Uyeda, 1965; Pollack et al., 1993; Stein, 1995). Internal thermal processes of the planet are directly or indirectly responsible for the generation of the geomagnetic field, convection in the mantle and outer core, movement of lithospheric plates, earthquakes and volcanism as well as formation of mineral and hydrocarbon deposits. Still today we have considerable uncertainty in our understanding of the exact values of the total thermal output of the Earth, and the internal sources and repositories of heat, which are primary parametres constraining the internal thermal regime and thermal evolution of the planet. In addition the hydraulic permeability is not easy to estimate for great depths, and it may well behave dynamically with time-dependent variations depending on the geodynamic setting (Ingebritsen and Manning, 2010).

The Heat and Mass Transfer session of the ICDP Conference 2013 in Potsdam received 23 contributions enlightening very different aspects of heat and mass transfer problems and the role of deep drilling in research. Understanding the processes of heat and mass transfer within the Earth is one of the key tasks in geoscience and has challenges in both pure science as well as in applications in energy production and raw materials exploration.

The topics and problems brought forward in the conference can be divided into the following groups:

1) Heat and mass transfer related to mantle plumes, mid-ocean ridges and subduction zones. These environments provide the active fields of heat and mass transfer and they can provide an 'endless' source of energy once the required technologies have been developed (Friðleifsson and Elders, 2005). Drilling is required to obtain deep in-situ information in these active conditions. Geochemical and isotope studies of magmatic products provide information on the source region of these rocks, and further on the heterogeneity of the mantle, and the nature of hot spots (De Paolo and Weis, 2007). Studies of mantle plume magmatism of hot-spot volcanoes and large igneous provinces could provide invaluable information on the origin and geochemical evolution of the deep-derived plume magmas, and enlighten the problems of mid-ocean-ridge basalt (MORB) vs. hot-spot volcanism, and the convective and metasomatic processes taking place in the upper and lower mantle and the mantle transition zone (DePaolo and Weis, 2007; Bercovici, 2012).

2) Molten and subsolidus intrusive complexes. The environment of molten rock is very demanding for sampling and drilling technologies, but only direct sampling of magma provides unbiased samples. Magma chambers cooling at shallow levels (< 5 km) are very interesting for developing technologies for extracting energy at very high temperatures (Elders et al., 2014b). On the other hand, drilling to layers beneath the brittle–ductile transition (about 2–5 km) but not to molten magma in volcanic areas provides a new potential method to extract geothermal energy with the already established EGS technology. Creating an artificial reservoir with brittle fractures wholly within the ductile zone prevents the typical loss of circulating heat transfer fluid, which improves the efficiency of the EGS. Furthermore, the method does not increase the pore pressure in the seismic brittle crust, thus avoiding artificially induced earthquakes. Drilling and downhole logging into the very high temperatures (approximately 500°C) still requires development of special high-temperature tools (Asanuma et al., 2012). Drilling into the magma itself would illustrate basic physical concepts of heat and mass transfer, and reveal geology from volcano structure to plate tectonic scales, and illustrate the excitement of scientific exploration in a previously unvisited extreme environment within our planet.

Figure 26. Inside the Solfatara volcano, Campi Flegrei, Italy

3) Active high-enthalpy systems are typically combinations of magmatic and hydrothermal processes. We need deeper understanding of these processes and need to develop methodologies and technologies for energy production in such systems both onshore and offshore (mid-oceanic ridges). Drilling to reservoirs with supercritical fluids is technologically very challenging (Axelsson et al., 2014), and reliable high-temperature logging and monitoring tools need to be developed.

ORE DEPOSITS

Volker Lüders, Robert Trumbull GFZ—German Research Centre for Geosciences, Germany

What are ore deposits?

Ore deposits are concentrations of metal-bearing rocks (ores) in the Earth´s crust. Ore deposits may form in all known geologic environments from the surface (Ni, Al, Fe oxides in laterite) to the deep mantle (diamonds in kimberlites). In cases where the ore grades are high enough, such metal concentrations form economic ore deposits which are exploited by surface or underground mining. Ore deposits have formed throughout Earth history and are still forming today, for example on the sea floor in submarine hydrothermal vents ('black smokers') or in terrestrial hot springs. Whereas some metallic ores form in many settings, e.g. Pb-Zn and Au-ores in magmatic-hydrothermal, hydrothermal, and sedimentary rocks, for others there are only a few important types of deposit. For example, most of the world´s copper production comes from porphyry copper deposits that formed from magmatic-hydrothermal fluids. The platinum group metals are almost exclusively hosted in mafic intrusive rocks, and by contrast, the largest manganese resources are related to sedimentary rocks.

Figure 27. Platinum

Strategic metals

In the recent past, ever-increasing demand for metals in industrial and emerging countries has led to a misbalance between supply and demand and thus to increasing prices on the world market. There are a number of so-called strategic metals (e.g. Cr, Sn, Cu, Nb, Ta, Co, Sb, as well as REE and PGE) which are indispensable for fast-growing, high-technology and 'green' economies. Many industrial nations are now dependent on imports of these metals from other countries, and there is great emphasis placed on securing long-term and ecologically sustainable supply. Apart from the socio-economic aspects of sustainable raw materials supply, there are major challenges ahead for the geoscience and minerals processing community. It can be said with some confidence that the 'easy' ore deposits have already been found and many have been completely extracted. The supply of strategic metals can only be partly met by recycling. New ore deposits will be needed in the foreseeable future, and this requires continued development of new technologies for efficient mining and ore processing, and for new tools for exploration, including drilling concepts.

Challenges for drilling

As in the oil and gas industry, drilling is well established and widely applied in the mining industry for exploration in order to find hidden ore bodies beneath physical or geochemical anomalies, and then to determine the 3D shape and extent of an ore body to estimate ore grades and reserves. Conventional drilling applications, however, only focus on exploration of ore bodies rather than on understanding their origin. Scientific drilling projects are therefore extremely important as they can provide new insights on ore-forming processes that may inspire new exploration models. Moreover, as near-surface economic deposits become harder and harder to find, exploration must target deeper crustal levels and this is a new frontier. Not much is known about the occurrence, geometry, ore grades and physical properties of deep-seated ore bodies. There are also many new challenges in drilling and logging technologies at great depth.

4) Active low-enthalpy geothermal systems. These environments are commonly used for energy production (for space heating), and there is increasing interest in using them for segregation of CO_2. The thermal structure of basins depends heavily on the thermal conductivity of rocks, and low thermal conductivity favors high temperatures at relatively shallow depth, though the heat flow does not need to be elevated. More should be known on the natural fluid flow in the subsurface medium, permeability structures, fluid geochemistry and temperature.

5) Monitoring and understanding of volcanic systems. Volcanic eruptions are among the biggest threats to human population. We cannot prevent future eruptions but we can improve our skills in predicting them. In this field, the monitoring of potentially dangerous volcanoes is necessary. Monitoring requires both surface and subsurface instrumentation. Deep drill holes are very important as they provide direct information on the heat and mass transfer in volcanoes. Drilling is also used to explore the efficiency and frequency of past volcanic activity (Nakada et al., 2005, Stolper et al., 2009; Shervais, 2009, 2013; DeNatale et al., 2011). The processes taking place in conduits, such as magma fragmentation or ash formation by explosive decompression and ash reactions in the atmopshere require further research (Spieler et al., 2004; Kueppers et al., 2006; Alidibirov and Dingwell, 2000).

6) Crustal heat flow and heat sources. Predicting deep crustal temperatures from shallow (1 km) heat flow and temperature data is perturbed globally by surface and near-surface processes, such as the palaeoclimatic conductive effects due to cycles of glaciations (about 100 ka; Kukkonen and Joeleht, 2003; Majorowicz and Šafanda, 2007; Majorowicz and Wybraniecz, 2010). Measurement of an undisturbed heat flow requires drilling to depths of more than 2 km. Therefore careful geothermal studies should be carried out in all deep drilling projects. Further, the distribution of heat producing elements (U, Th, K) in the crust, mantle and the whole Earth remains a challenge. There are still considerable uncertainties in the total heat budget of the Earth and the quantitative role of heat producing elements in it (Dye, 2012; Davies and Davies, 2005). Further, thermal transport properties of rocks are an important component in heat and mass transfer in the crust and upper mantle, and more needs to be known of them at high temperatures and pressures.

7) Mineral resources and environmental issues of mining. Our civilisation is built on mineral and energy resources (e.g. Craig et al., 2010). The present mining industry is using deposits at a rate about an order of magnitude faster than a couple of generations ago. This is a huge challenge for the methods and efficiency of exploration, especially as exploration targets tend to be deeper than before. We still need to understand better the genesis and formation of mineral deposits, especially those of the metals becoming critical in modern technologies (e.g. REE metals, Walters et al., 2013), but not to forget the base metals either. With increasing scale of mining, environmental prob-

Figure 28. Platinum metals mined at a large scale in the Bushveld Complex of South Africa.

lems arise unless appropriate actions are taken. Processing of toxic mine waste and waters (Akcil and Koldas, 2005) requires new technologies (e.g. microbial processing) to generate closed fluid circulation systems with minimum environmental impacts. Deep and super-deep drilling is needed in studying the thermal and hydrogeological conditions in the mine camps (Ntholi and de Wit, 2012).

8) Geodynamic issues of heat and mass transfer. Driving forces moving the plates and the basic mechanism generating plate tectonics on the whole are still matters of debate, and more needs to be known in these fields. What is the actual connection between mantle convection and movement of the surface plates, and further, are the ridge-push, slab-pull and asthenosphere drag forces well constrained? The apparently weak plate boundaries and zones of deformation preserved at plate boundaries for times much longer than the deformation has taken place require coupled processes of lithospheric weakening, shear localisation, grain size evolution and damage which are not yet fully understood (Tackley, 2000; MacKenzie, 2001; Bercovici, 2003, 2012). Understanding orogenesis is one fundamental question in geology and geophysics, and deep drilling into past and present brittle and ductile deformation zones of orogenic belts may essentially help at critical sites (e.g., Gee et al., 2010; Lorenz et al., 2011). Depending on the problem studied the timescale of heat and mass transfer may require rapid actions, for instance drilling into earthquake faults to find out the frictional heat released in an earthquake (Brodsky et al., 2009, 2010). Similar situations may apply to active volcanic and magmatic systems.

Future scientific targets

In summary, the main tasks requiring more research and activity in heat and mass transfer are as follows:

- studying heat and mass transfer in active volcanic and magmatic environments
- developing and applying technologies for drilling into very high temperatures
- properties of super-critical fluid systems
- heat and mass transfer in low-enthalpy environments
- determination of undisturbed crustal heat-flow values in normal stabilised crust
- distribution and concentrations of heat-producing elements in the crust and mantle
- understanding heat and mass transfer in genesis of mineral deposits
- heat and mass-transport properties of rocks as functions of temperature and pressure.

Drilling issues

Drilling in extremely hot environments of high-enthalpy systems with supercritical fluids is an important challenge, and requires special materials and alloys in drill pipes and bits as well as enforcing strict safety measures. Moreover, downhole geophysical and hydrogeological tools must have exceptional tolerance at high temperatures and pressures and durability in chemically aggressive fluid environments.

Figure 29. Sampling a Kilauea lava flow on Hawai'I

In active magmatic environments, the risk of accidentally drilling in to magma should be decreased, developing and applying sonic and seismic tools for ahead-directed sounding during drilling. Recognising the roof of a magma chamber well before drill hole penetrates it would allow careful planning how to proceed. Coring of magma requires special cooling and quenching measures. Experience in magma sampling in drilling is still very limited, and needs further development.

Fracking in low-enthalpy geothermal projects is a prerequisite for enhancing the in-situ hydraulic permeability for efficient fluid circulation. However, the anisotropic character of the sedimentary or crystalline reservoir rocks, pre-existing fracture systems and the orientation of the natural stress field all challenge the technology. It is very important from the societal point of view and the acceptance of the geothermal energy production that fracking is a controlled process to not trigger earthquakes above an acceptable magnitude.

Drilling costs can be decreased with modern hydraulic drilling rigs and technologies where the manpower is minimised, and drilling efficiency is maximised. Further new drilling technologies and innovations, such as deep water-hammer drilling, should be tested.

Drilling super-deep holes of about 10 km would remarkably increase our understanding of the heat and mass transfer processes in the crust and the brittle–ductile transition. The present plans to drill into the oceanic Moho (at about 6 km; Ildefonse et al., 2007) and a research borehole to 10 km depth from 3 to 4 km deep mines in South Africa (Ntholi and de Wit, 2012) are good examples of ambitious drilling projects which will be in the spotlight of geosciences if carried out. Super-deep drilling with drilling goals at depths of over 10 km are still technological and scientific adventures, where new methods and technologies need to be developed. Both the Kola super-deep hole in Russia and the KTB super-deep hole in Germany failed to reach their original depth targets mainly due to difficulties in penetrating rocks with significant shearing and weakness and rheological properties close to brittle–ductile transition. One of the problems was the underestimated temperature determined from extrapolating thermal data from shallow boreholes. Reaching such great depth requires also improved downhole drilling engines for maximum efficiency and torque in drilling.

Recommendations

Heat and mass-transfer issues are related to almost every scientific drilling project, and ICDP should be careful in checking possibilities to enhance this field as independent heat and mass-transfer motivated projects as well as a 'piggy-back' contributions from projects aimed at other fields.

References

Akcil A. and Koldas S., 2005. Acid mine drainage (AMD): causes, treatment and case studies. Journal of Cleaner Production 14:1139–45.

Alidibirov, M. and Dingwell, D. B., 2000. Three fragmentation mechanisms for highly viscous magma under rapid decompression. Journal of Volcanology and Geothermal Research, 100, 413–421.

Asanuma, H., Muraoka, H., Tsuchiya, N., and Ito, H., 2012. The Concept of the Japan Beyond-Brittle Project (JBBP) to Develop EGS Reservoirs in Ductile Zones. GRC Transactions, Vol. 36, 2012.

Axelsson, G.; Egilson, T.; Gylfadóttir, S. S. (2014): Modelling of temperature conditions near the bottom of well IDDP-1 in Krafla, Northeast Iceland., 10.1016/j.geothermics.2013.05.003 Geothermics 49 49–57

Bahlburg H.; Weiss R.; Wünnemann K. (2010): Low energy deposition in the Chicxulub crater during the impact to post-impact transition. Earth and Planetary Science Letters

Beltrami, H., 2002. Earth's Long-Term Memory. Science 297, 206–207.

Bercovici, D. 2003. The generation of plate tectonics from mantle convection. Earth and Planetary Science Letters, 205, 107–121.

Bercovici, D. 2012. Mantle convection. In: Harsh Gupta (ed.), Encyclopedia of Solid Earth Geophysics, Springer, 1–27.

Brodsky, E. E., Ma, K., Mori, J., Saffer, D. (2009): Rapid Response Fault Drilling Past, Present, and Future. Scientific Drilling, 8:66–74.

Brodsky, E. E., Mori, J., Fulton, P. M. (2010): Drilling Into Faults Quickly After Earthquakes. EOS 91(27):237–238.

Buettner, G.; Huenges, E. (2002): The heat transfer in the region of the Mauna Kea (Hawaii)—constraints from borehole temperature measurements and coupled thermo-hydraulic modelling., Tectonophysics, 371, 23–40.

Cermak, V.; Bodri, L.; Safanda, J. (2009): idal modulation of temperature oscillations monitored in borehole Yaxcopoil-1 (Yucatán, Mexico)., Earth and Planetary Science Letters 282 131–139

Chang, C.; Haimson, B. (2005): Non-dilatant deformation and failure mechanism in two Long Valley Caldera rocks under true triaxial compression. International Journal of Rock Mechanics and Mining 42(3) 402–414.

Clauser, C., Giese, P., Huenges, E., Kohl, T., Lehmann, H., Rybach, L., Šafanda, J., Wilhelm, H., Windloff, K. and Zoth, G., 1997. The thermal regime of the crystalline continental crust: Implications from the KTB. J. Geophys. Res., 102, no. B8, 18417–18441.

Convection Models. In: The History and Dynamics of Global Plate Motions, Geophysical Monograph 121, Copyright 2000 by the American Geophysical Union, pp. 47–71.

Craig J. R., Vaughan D. J. and Skinner B. J., 2010. Earth resources and the environment. Prentice Hall.

Dallimore, S. R.; Collett, T. S.; Taylor, A. E.; Uchida, T.; Weber, M. H.; Chandra, A.; Mroz, T. H.; Caddel, E. M.; Inoue, T. (2005): Scientific Results from the Mallik 2002 Gas Hydrate Production Research Well Programme, Mackenzie Delta, Northwest Territories, Canada., Geological Survey of Canada, Bulletin 585, 72pp.

Davies, J. H. and Davies, D. R., 2010. Earth´s surface heat flux. Sold Earth, 1, 5–24.

De Natale, G., Troise, C., and Sacchi, M. , 2011. The Campi Flegrei Deep Drilling Project., Scientific Drilling, 4, 48–50.

De Natale, G., Troise, C., Pingue, F., Mastrolorenzo, G., Pappalardo, L., Battaglia, M., and Boschi, E. (2006), The Campi Flegrei caldera: unrest mechanisms and hazards in Mechanisms of Activity & Unrest at Large Calderas, edited by C. Troise, De Natale, G., and Kilburn, C. R. J., pp. 25–44, Geological Society of London.

DePaolo, D. J. and Weis, D., 2007. Hotspot Volcanoes and Large Igneous Provinces. In: Harms, U. et al., ed., Continental Scientific Drilling: A Decade of Progress and Challenges for the Future. Springer-Verlag, 366 pp.

Dye, 2012. Geoneutrinos and the radioactive power of the Earth. Reviews of Geophysics, RG3007, 50, 19 p.

Elders, W. A.; Friðleifsson, G. Ó.; Albertsson, A. (2014b): Drilling into magma and the implications of the Iceland Deep Drilling Project (IDDP) for high-temperature geothermal systems worldwide., 10.1016/j.geothermics.2013.05.001, Geothermics 49 111–118.

Elders, W. A.; Friðleifsson, G. Ó.; Pálsson, B. (2014a): Iceland Deep Drilling Project: The first well, IDDP-1, drilled into magma., 10.1016/j.geothermics.2013.08.012, Geothermics 49, 1.

Ferrière, L.; Koeberl, C.; Ivanov, B. A.; Reimold, W. U. (2008): Rocks, Shock Attenuation, and Uplift Formation Shock Metamorphism of Bosumtwi Impact Crater., 10.1126/science.1166283 Science 322 1678.

Friðleifsson, G. Ó., Elders, W. A.,2005. The Iceland Deep Drilling Project: a search for deep unconventional geothermal resources. Geothermics 34, 269–285.

Friðleifsson, G. Ó., Pálsson, B., Albertsson, A. L., Stefánsson, B., Gunnlaugsson, E., Ketilsson, J. and Gíslason, Þ., 2015. IDDP-1 Drilled into Magma—World´s First Magma-EGS System Created. Proceedings World Geothermal Congress 2015. Melbourne, Australia, 19–25 April, 2015.

Gee, D. G, Juhlin, C., Pascal, C., Robinson, P. ,2010,. Collisional Orogeny in the Scandinavian Caledonides (COSC)., 10.1080/11035891003759188. GFF 132(1) 29–44.

Gondwe, B. R. N.; Lerer, S.; Stisen, S.; Marín, L.; Rebolledo-Vieyra, M.; Merediz-Alonso, G.; Bauer-Gottwein, P. (2010): Hydrogeology of the south-eastern Yucatan Peninsula: New insights from water level measurements, geochemistry, geophysics and remote sensing., 10.1016/j.jhydrol.2010.04.044, Journal of Hydrology

Harms, U. and Emmermann, R., 2007. History and status of the International Continental Scientific Drilling Programme. In: U. Harms, C. Koeberl and M. D. Zoback (eds.), Continental Scientific Drilling, Spriger, Berlin, pp. 1–52.

Hauksson, T., Markússon, S., Einarsson, K., Karlsdóttir, S. N., Einarsson, A., Möller, A., Sigmarsson, Th., 2014. Pilot testing of handling the fluids from the IDDP-1 exploratory geothermal well, Krafla, N. E. Iceland. Geothermics 49, 76–82.

Hjartarson, S.; Sævarsdóttir, G.; Ingason, K, Pálsson, B.; Harvey, W. S.; Pálsson, H. (2014): Utilisation of the chloride bearing, superheated steam from IDDP-1., 10.1016/j.geo-thermics.2013.08.008, Geothermics 49 83–89.

Huang, S.P., H.N. Pollack, and P.Y. Shen, 2000: Temperature trends over the past five centuries reconstructed from borehole temperatures. Nature, 403, 756–758.

Ildefonse, B. , Christie, D. M. and the Mission Moho Workshop Steering Committee, 2007. Mission Moho Workshop: Drilling Through the Oceanic Crust to the Mantle. Scientific Drilling, No. 4, March 2007, 11–18.

Ingebritsen, S. E. and Manning, C. E., 2010. Permeability of the continental crust: dynamic variations inferred from seismicity and metamorphism. Geofluids, 10, 193–205, doi: 10.1111/j.1468-8123.2010.00278.x

Kessler, J. A. (2013): First Results from HOTSPOT: The Snake River Plain Project, Idaho, U.S.A., 10.2204/iodp.sd.15.06.2013, Scientific Drilling, 15,35–45.

Kremenetsky, A. A. and Ovchinnikov, L. N., 1986. The Precambrian continental crust: Its structure, composition and evolution as revealed by deep drilling in the USSR. Precambrian Res., 33: 11–43.

Kueppers, U., Scheu, B., Spieler, O., Dingwell, D. B., 2006. Fragmentation efficiency of explosive volcanic eruptions: A study of experimentally generated pyroclasts. Journal of Volcanology and Geothermal Research, 153, 125–135

Kukkonen, I. T. and Jõeleht, 2003. Weichselian temperatures from geothermal heat flow data. Journal of Geophysical Research, 108 (B3), ETG-9, 11 p.

Kukkonen, I. T., Rath, V., Kivekäs, L., Safanda J. and Cermak, V., 2011. Geothermal studies of the the Outokumpu Deep Drill Hole: Vertical variation in heat flow and palaoeclimatic implications. Physics of the Earth and Planetary Interiors, 188, 9–25.

Lee, W. H. K and Uyeda, S., 1965. Review of heat flow data. In: W. H. K. Lee (ed.), Terrestrial Heat Flow, AGU, Washington, D. C., pp. 87–190.

Lorenz, H., Gee, D. and Juhlin, C., 2011. The Scandinavian Caledonides-Scientific Drilling at Mid-Crustal Level in a Palaeozoic Major Collisional Orogen. Scientific Drilling, 11, 60–63.

MacKenzie K., 2001. Evidence for a plate tectonics debate. Earth Science Reviews, 55, 235–336.

Maharaj, D, Elbra, T and Pesonen, L. J., 2013. Physical Properties of the Drill Core from the El'gygytgyn Impact Structure, NE Russia. Meteoritics and Planetary Science, v. 48 (7), 1130–1142.

Majorowicz, J., Šafanda, J., 2007. Heat flow variation with depth in Poland: evidence from equilibrium temperature logs in 2.9 km-deep well Torun-1. Int. J. Earth Sci. (Geol. Rundsch.). doi:10.1007/s00531-007-0210-2.

Majorowicz, J., Wybraniec, S., 2010. New terrestrial heat flow map of Europe after regional paleoclimatic correction application. Int. J. Earth Sci.. doi:10.1007/s00531-010-0526-1.

Markússon, S. and Hauksson, T., 2015. Utilisation of hottest well in the world, IDDP-1 in Krafla. Proceedings World Geothermal Congress 2015. Melbourne, Australia, 19–25 April, 2015.

McConnell, V. S.; Roach, A. L.; Priest, S. S, Sass, J. H. (1999): Long Valley Coring Project, 1998 —Preliminary Stratigraphy and Images of Recorded Core., USGS Open File Report 99–158

Mottaghy, D., Schellschmidt, R., Popov, Yu. A., Clauser, C., Kukkonen, I. T., Nover, G., Milanovsky, S., Romushkevich, R. A., 2005. New heat flow data from the immediate vicinity of the Kola super-deep borehole: Vertical variation in heat flow confirmed and attributed to advection. Tectonophysics, vol. 401, 119–142.

Nakada, S., Uto, K., Sakuma, S., Eigelberger, J. C., Shimizu, H., 2005. Scientific results of conduit drilling in the Unzen Scientific Drillng Project. Scientific Drilling 1: 18–22, doi:102204/iodp.sd.1.03.2005.

Ntholi, T. and de Wit, M., 2012. Technical and socio-economic feasibility of the Passive Underground Mine-water Purification (PUMP) model. Inkaba yeAfrica: 9th Annual Workshop, Germany—2012 (abstract).

Pollack, H. N., Hurter, S. J., and Johnson, J. R.: Heat-Flow from the Earth's Interior—Analysis of the Global Data Set, Rev. Geophys., 31, 267–280, 1993.

Pollack, H. N., and J. E. Smerdon, 2004: Borehole climate reconstructions: Spatial structure and hemispheric averages. J. Geophys. Res., 109(D11), D11106, doi:10.1029/2003JD004163.

Šafanda, J., Szewczyk, J. and Majorowicz, J., 2004. Geothermal evidence of very low glacial temperatures on a rim of the Fennoscandian ice sheet. Geophysical Research Letters, 31, L07211, doi:10.1029/2004GL019547.

Šafanda, J.; Heidinger, P.; Wilhelm, H.; Cermak, V. (2005): Fluid convection observed from temperature logs in the karst formation of the Yucatan Peninsula, Mexico., Journal of Geophysics and Engineering 2(4) 326–331

Šafanda, J.; Wilhelm, H.; Heidinger, P.; Cermák, V. (2009): Interpretation and mathematical modeling of temporal changes of temperature observed in borehole Yaxcopoil-1 within the Chicxulub impact structure, Mexico., Journal of Hydrology 372 9–16

Shervais, J.W.; Evans, J.P. (2014): Drilling Into the Track of the Yellowstone Hot Spot., Eos, Transactions, American Geophysical Union 95(10) 85–86.

Shervais, J. W.; Schmitt, D. R.; Nielson, D.; Evans, J. P.; Christiansen, E. H.; Morgan, L.; Shanks, W. C. P.; Prokopenko, A. A.; Lachmar, T.; Liberty, L. M.; Blackwell, D. D.; Glen, J. M.; Champion, D.; Potter, K. E., Stolper, E.; DePaolo, D.; Thomas, D. (2009): Deep Drilling into a Mantle Plume Volcano: The Hawaii Scientific Drilling Project., Scientific Drilling, 7, 4–14.

Shervais, J. W.; Schmitt, D. R.; Nielson, D.; Evans, J. P.; Christiansen, E. H.; Morgan, L.; Shanks, W. C. P.; Prokopenko, A. A.; Lachmar, T.; Liberty, L. M.; Blackwell, D. D.; Glen, J. M.; Champion, D.; Potter, K. E.; Kessler, J. A. (2013): First Results from HOTSPOT: The Snake River Plain Project, Idaho, U.S.A., 10.2204/iodp.sd.15.06.2013, Scientific Drilling, 15, 35–45.

Spieler, O., Kennedy,, B., Kueppers, U., Dingwell, D. B., Scheu, B., Taddeucci, J., 2004 The fragmentation threshold of pyroclastic rocks. Earth and Planetary Science Letters 226, 139–148.

Stein, C. A., 1995. Heat flow of the Earth. In: T. J. Ahrens (ed.), AGU Reference Shelf 1, Global Earth Physics, A Handbook of Physical Constants, AGU, Washington DC, pp. 144–158.

Stolper, E.; DePaolo, D.; Thomas, D. (2009): Deep Drilling into a Mantle Plume Volcano: The Hawaii Scientific Drilling Project., Scientific Drilling, 7, 4–14.

Tackley, P. J., 2000. The Quest for Self-Consistent Generation of Plate Tectonics in Mantle

Thomas, D. M., Paillet, F. and Conrad, M., 1996. Hydrogeology of the Hawaii Scientific Drilling Project borehole KP-1: 2. Groundwater geochemistry and regional flow patterns. J. Geophys. Res., 101:11683–11694, doi: 10.1029/95JB03845.

Vidal, O., Goffé, B. and Arndt, N., 2013.Metals for a low-carbon society. Nature Geoscience, 6, 894–896.

Walters, A. S., Goodenough, K. M., Hughes, H. S. R., Roberts, N. M. W., Gunn, A. G., Rushton, J. AND Lacinska, A. 2013. Enrichment of Rare Earth Elements during magmatic and post-magmatic processes: a case study from the Loch Loyal Syenite Complex, northern Scotland. Contributions to Mineralogy and Petrology, 10.1007/s00410-013-0916-z .

Wilhelm, H.; Heidinger, P.; Šafanda, J.; Cermák, V.; Burkhardt, H.; Popov, Yu. (2004): High resolution temperature measurements in the borehole Yaxcopoil-1, Mexico., Meteoritics and Planetary Science 39(6) 813–819.

THE UBIQUITOUS HIDDEN BIOSPHERE

Jens Kallmeyer GFZ — German Research Centre for Geosciences, Germany
Tom Kieft Department of Biology, New Mexico Tech, Socorro, USA

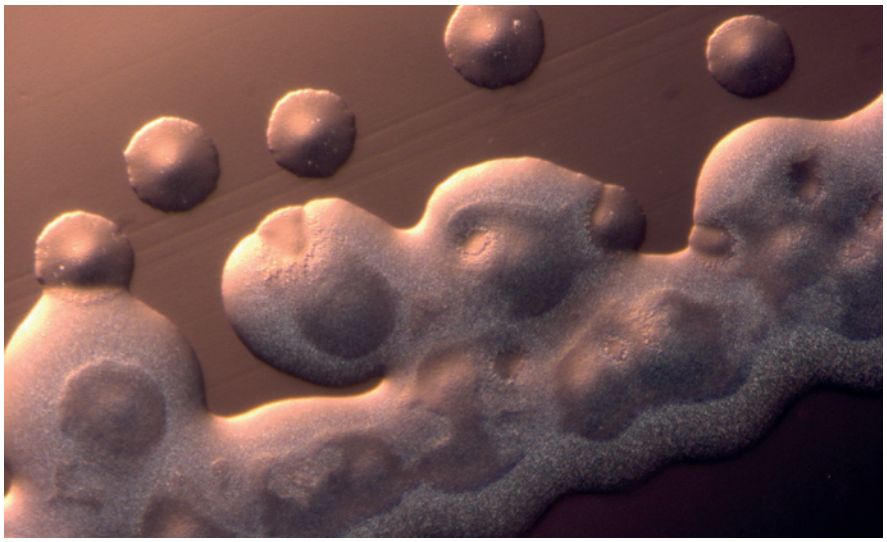


Figure 30. Light microscopic picture of discrete methanotrophic colonies (brown) partially overgrown by contaminants (whitish); stereo microscope, magnification: 25×

Lay of the land

Over the last two decades, exploration of the deep subsurface biosphere has developed into a major research field in both earth sciences and environmental biosciences. It is now commonly accepted that the deep subsurface biosphere forms the largest ecosystem on Earth. Despite recent studies that significantly downsized estimates of the number of microbial cells and its biomass (Kallmeyer et al., 2012), the deep biosphere still harbours a significant part of all life on Earth and is a key driver of global biogeochemical cycles (Jørgensen, 2012).

Microbial life in the subsurface has a profound impact on human activity, even though the 'key players' remain invisible to the naked eye. For example, natural gas of biogenic origin occurs in economically producible quantities in some sedimentary basins e.g. the Po Basin, Italy.

The same type of gas, occurring at shallower depths in all sedimentary basins, can enter the hydrosphere or atmosphere. Depending on the local conditions, the gas is either consumed or becomes a greenhouse gas.

Sweet crude oils can be converted into viscous fluids that are difficult to produce, thanks to selective biodegrada-

tion by microorganisms in underground reservoirs—here the deep biosphere is downgrading a natural energy resource. Understanding the mechanisms of microbially mediated processes is crucial not just for reducing risk in exploration and production but also to understand the coupling and fluxes between the geosphere on one side and the hydrosphere and atmosphere on the other. Also, in several areas of the world, groundwater is affected by geogenic pollution. The liberation and precipitation of these pollutants is controlled by microbial activity.

Speaking generally, the demands of a growing global population cannot be met without utilising the deep subsurface, either as a resource or as a repository. A good knowledge of the microbial communities themselves and, more importantly, their influence on the cycling of elements will be crucial to achieve these goals. As access to the deep subsurface is only possible by drilling, the ICDP plays an important role in our quest to explore the deep subsurface biosphere. Perhaps the most crucial issue for any deep biosphere study is the availability of uncontaminated samples. This is not much of a concern for commercial drilling operations, so ICDP becomes the prime source for suitable sample material.

Past accomplishments in ICDP

The study of the deep continental biosphere has matured considerably in recent years, due in part to the ICDP's efforts to integrate deep life studies into drilling projects. At its inception in 1994, the ICDP recognised that pursuit of the then new field of subsurface geomicrobiology could be facilitated by drilling projects (Zoback and Emmermann, 1994). This theme was examined in both theoretical and practical terms in the 2005 ICDP Science Plan (Horsfield et al., 2006), at a 2009 ICDP workshop focused on the Deep Biosphere (Mangelsdorf and Kallmeyer, 2010), and now at the 2013 ICDP Scientific Conference, where 'the hidden biosphere' was afforded a prominent role. Biological studies have been carried out as part of ICDP drilling research projects planned for other purposes including the Mallik Gas Hydrate Research Project (Colwell et al., 2005), the Chesapeake Bay impact crater study (Gohn et al. 2008), and more shallow sedimentary paleoclimate lake drilling projects (e.g. Lake Van, Glombitza et al., 2013; Lake Potrok Aike, Vuillemin and Ariztegui, 2013). Frontier exploration of the deep biosphere was spearheaded by IODP and its predecessor ODP; several dedicated deep biosphere cruises were carried out and deep life studies are now being incorporated into many expeditions. By comparison, ICDP's involvement has been small, despite there being a much broader range of targets and extreme environments in continental settings.

Fundamental open questions

A number of overarching deep life research questions have been identified (Horsfield et al., 2006; Mangelsdorf and Kallmeyer, 2010). These are listed below, each with a summary of the current state of knowledge.

1) What is the extent and diversity of deep microbial life and what are the factors limiting it? The continental subsurface has been estimated to contain $0.25–2.5 \times 10^{29}$ prokaryotic cells (bacteria and archaea) (Whitman et al., 1998), or 0.8–27% of the Earth's total prokaryotes (Kallmeyer et al., 2012). The factors that potentially limit the maximum depth limit for life include temperature, pressure, energy availability, and availability of fluid-filled pore space of sufficient size and permeability. Of these, temperature is the least forgiving with a currently understood upper limit for life of about 122°C (Takai et al., 2008). Factors other than temperature are also likely to come into play, as evidenced by patterns in petroleum reservoirs, where microbial activities sharply diminish as temperatures exceed about 80°C (Wilhelms et al., 2001). Energetic requirements for microbial maintenance and repair increase at elevated temperatures, including the need to replace proteins as amino acids racemise (Onstott et al., 2014), and so energy availability may be extremely important. The depth limit of the biosphere has yet to be delineated. Subsurface biodiversity has also not been fully characterised; microbial communities in deep subsurface continental habitats examined to date are diverse and vary with geochemical conditions (Gihring et al., 2006). Culture-independent, nucleic-acid-based surveys have revealed novel lineages (Takai et al., 2001; Gihring et al., 2006; Chivian et al., 2008, Sahl et al., 2008), many of which appear to be unique to subsurface environments.

2) What are the types of metabolism / carbon / energy sources and the rates of subsurface activity? Many subsurface microbial ecosystems are fuelled by organic carbon that was generated by photosynthesis and then buried or transported to deeper layers; however, the quantity and quality of the organic matter diminishes with depth. Some microbes in the deeper, more remote regions of the subsurface have been shown to utilise alternative energy sources like H_2, CO, and short-chain hydrocarbons ('geogas', Pedersen, 2000) generated by rock–water interactions, e.g., serpentinisation (Schrenk et al., 2013) and radiolysis of water (Chivian et al., 2008). The importance of geogas relative to photosynthetically derived buried organic matter has yet to be determined; the metabolic diversity of subsurface microbes requires further exploration, as well. Rates of subsurface metabolism estimated through geochemical modelling are orders of magnitude slower than those measured in surface habitats or pure cultures (Phelps et al., 1994; Kieft and Phelps, 1997), but actual in-situ rates are poorly constrained due to technical limitations.

3) How is deep microbial life adapted to subsurface conditions? The deep subsurface imposes high temperature and high pressure, generally combined with low energy fluxes, thus requiring unique physiological adaptations. Most of these remain poorly understood, in part due to our current inability to cultivate the majority of subsurface microbes in the laboratory. The rise of genomic, transcriptomic, and metabolomic approaches will no doubt generate new

Figure 31. Fluorescence of hydrocarbon fractions

discoveries in this area. Still, as deep subsurface samples are usually characterised by extremely low biomass and the presence of inhibitory substances, most molecular techniques have to be modified in order to work with such samples.

4) How do subsurface microbial communities affect energy resources? Subsurface microbes can generate energetically useful products, e.g., H_2 and methane; they can also degrade hydrocarbons in petroleum reservoirs (Head et al., 2003). We need a better understanding of these processes and the factors governing them.

5) How does the deep biosphere interact with the geosphere and atmosphere? Deep subsurface microbial communities are metabolically active, albeit at slow rates (Kieft and Phelps, 1997), and as such they strongly influence the chemistry and mineralogy of their surroundings. They can dissolve or precipitate minerals, thereby affecting porosity and permeability. Their metabolic processes likely also affect fluxes between the subsurface and the atmosphere. For example, sub-seafloor microbes remove 50–80% of H_2 before it can be released from diffuse hydrothermal vents to overlying water. Continental subsurface microbes likely mediate similar processes.

6) Can we use the subsurface biosphere as a model for life on early Earth or other planets? Life on Earth could have originated in the subsurface, where elevated temperatures, mineral surfaces, and abiotic generation of simple organic compounds occur; the subsurface could also have provided a refuge for early life from the Hadean bombardment. Beyond Earth, conditions in the subsurface of other planets and planetary bodies in our solar system and elsewhere may be more habitable than those at the surface, and if the geology is right, then geogas might be present as a potential subsurface energy source for microbes. Further drilling on Earth may inform our decisions about exploring other planets.

Future scientific targets

The above are broad, enduring questions similar to those posed by other groups, e.g., IODP, the Deep Carbon Observatory (http://DCO.net), and Colwell and D'Hondt (2013). They need to be addressed by multidisciplinary research projects that drill into subsurface environments with wide-ranging geologies. Deep biosphere studies entail not only geomicrobiology e.g. (Baker et al., 2003, Pedersen, 2000), but also biogeochemistry (e.g. Zink et al., 2003), numerical modelling (Horsfield et al., 2006) and even geophysical phenomena, e.g., the release of hydrogen or methane gas by seismic events (Bräuer et al., 2005; Sleep and Zoback, 2007). The variety of physical/chemical conditions beneath the the Earth's surface produce a variety of biological phenomena, described above under Fundamental Open Questions, that demand study. In fact, the continental subsurface is more geologically diverse than the marine subsurface, and thus deep continental microorganisms are likely even more diverse than those beneath the oceans, and so ideally, they deserve an even greater scientific drilling programme.

Upcoming ICDP projects deal with a variety of scientific topics in which geomicrobiology combined with biogeochemistry features strongly:

• **Deep hardrock microbiology.** One example is the COSC Project (Sweden), drilled in Summer 2014. The project is primarily geophysical and addresses questions related to mountain belt dynamics, but drilling at this site is also enabling key geomicrobiological questions to be addressed. Foremost among these is, what is the relative importance of surface-derived organic matter from photosynthesis compared to H_2 generated by rock–water interactions, e.g., oxidation of ultramafic rocks and radiolysis of water, as energy sources for fracture-water microbial communities? In the past, other projects have worked on similar research topics using short horizontal drilling from inside mines (Chivian et al., 2008) and other underground facilities (Pedersen, 2000). Right now there are no such projects scheduled, but in the event that a science-friendly facility allows long-term access, a project could be initiated relatively quickly.

• **Shallow (100 m) sediment and groundwater geochemistry.** A pilot study in Illinois (USA) was conducted in summer 2014 for the upcoming IDRAS project in Southeast Asia. The motivation for this project is to understand the spatial distribution and controlling factors of elevated arsenic levels in Southeast Asian groundwater, which affects over 100 million people. Although the exact mechanisms have not yet been identified, there is broad agreement that microbial activity plays an important role. Recovery of uncontaminated drill cores from relatively coarse aquifer sands will be a major technical challenge.

• **Metalliferous sediments** are scheduled to be drilled at Lake Towuti (Sulawesi, Indonesia) in 2015. The overall aim of this drilling project is to understand the climatic evolution of the Indo-Pacific Warm Pool over the last 500 thousand years. This area is crucially important for our understanding of global climate dynamics but so far there are no long records from this area (Russel and Bijaksana, 2012). Although the Lake Towuti project is driven by paleoclimate research, it has a strong geomicrobiology component with six groups participating. The sediments offer the opportunity to study microbial metal cycling in much greater detail than in metal-poor sediments.

• **Serpentinisation.** The Oman Ophiolite drilling project is being developed to study the microbiology and geochemistry of serpentenizing rocks and high-pH environments. The project is mainly carbon sequestration motivated, but will have a geomicrobiology component. Serpentinisation releases H_2, which can be metaboilised by micro-organisms.

• **Geothermal environments.** To date the geothermal projects in ICDP, such as the Iceland geothermal project (Friðleifsson and Elders, 2007), have not had a microbiological component, this being due to the high enthalpy of the system under study. However, new projects, e.g. Mutnovsky Volcano may

THE LIVING UNDERGROUND

Karsten Pedersen Microbial Analytics Sweden AB (MICANS), Mölnlycke, Sweden

The deep biosphere

Exploration of the microbial world got off to a slow start some 350 years ago, when Leeuwenhoek and his contemporaries focused their microscopes on very small life forms.
It was not until about 20 years ago, however, that exploration of the world of underground microbes gathered momentum. In the mid-1980s, the drilling of deep holes for scientific research started. Holes up to thousands of metres deep were drilled in hard as well as sedimentary rock, and up came microbes in numbers equivalent to what could be found in many surface ecosystems. Until then, it had been a general concept that all life on Earth depends on the sun via photosynthesis. This concept has now changed because the deep subterranean biosphere under the sea floor and the continents is driven by the energy available in hydrogen and methane, sulphur and iron expelled from the interior of our planet. In other words, a sun is not needed to sustain life on Earth! Knowledge about this deep biosphere has just begun to emerge and is expanding the spatial borders for life from a thin layer on the surface of the planet Earth and in the seas to a several kilometre-thick biosphere reaching deep below the ground surface and the sea floor. Life has been present and active deep down in Earth for a very long time and it cannot be excluded that the location of the origin of life was a deep subterranean aquifer environment (probably hot with a high pressure) rather than a shallow, lukewarm pool environment on the surface of earth.

The origin of life

Life in the early days of our planet would have been protected from meteoritic impacts, ultraviolet irradiation, volcanic eruptions and desiccation in underground environments. An underground origin of life has become plausible because the underground offers infinite possibilities for the mixing of water with various chemical and physical conditions, one of which might have been the correct mix for life to start. Additionally, the underground was rich in minerals with metals that may have catalysed many chemical reactions preceding the origin of life and that are still used as obligate catalytic components in many of the enzymes ruling the metabolic pathways of cellular life. The figure shows an arbitrary series of mixing of water with varying properties, demonstrating the outstanding environmental variability underground, compared to rather homogenous surface environment such as the sea and lakes.

Key challenge

Whether the right conditions actually existed for an underground origin of life remains to be tested and proven. Scientific deep drilling will make it possible to reach deep environments that no one has studied before. Maybe there, deep under our feet, the key to our understanding of the origin of life awaits discovery?

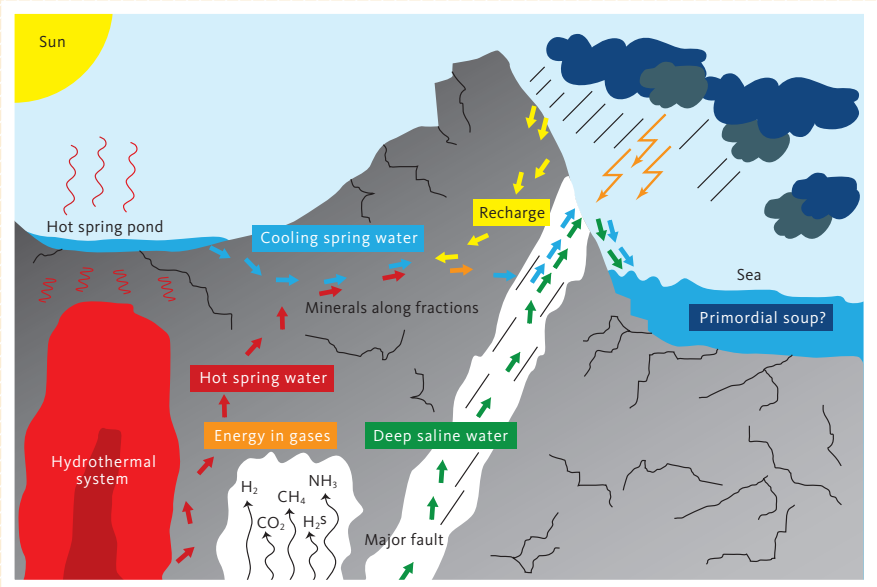


Figure 32. Environmental variability of the underground

bring the opportunity to explore such ecosystems.

• **Biodegradation of hydrocarbons** is a topic of major ecological and economic importance. Given the increased industrial interest in this topic, potential industry collaboration might be possible.

• **Mud volcanoes** are windows to the deep biosphere by delivering material from greater depth to the surface. However, this material usually becomes contaminated on its way up, due to inflowing aquifers etc. Drilling into an active mud volcano would allow direct access to uncontaminated samples in order to study biogenic and thermogenic hydrocarbon-generating processes.

There are many other scientific questions, for example about the response of microbial life on anthropogenic alteration of a subsurface habitat that could be addressed by drilling, although there are currently no scheduled or planned ICDP projects in these research areas.

Drilling issues

The simplest way to further expand deep life studies sponsored by the ICDP is to add geomicrobiological and geochemical components to even more of the planned and imminent IODP drilling projects, possibly to all projects. These 'piggy-backing' studies have always been encouraged by the ICDP, and suggestions have been forthcoming as to how to put these wishes into practice (Horsfield et al., 2007), but in fact, there are built-in challenges. Some of these challenges have to do with conflicting sample needs or at least the perception of conflicts. For example, paleoclimatologists require complete continuous depth profiles, with their core remaining undisturbed in core liners, while biologists need to sub-sample the core as soon as possible after retrieval, ideally at the drill site in order to preserve the indigenous microbial population and to obtain accurate information about the porewater composition. The addition of an extra borehole to a lake project adds expense, but may be justified by compelling scientific questions. Adding depth to a borehole, e.g., drilling/coring into bedrock underlying lake sediments could add a deep-life context to a palaeoclimate study at relatively modest extra cost. The need to subsample on-site, usually in an anaerobic chamber, has been addressed in the IODP by always having this equipment aboard the drill ship; GFZ Potsdam has a mobile geomicrobiological laboratory (BUGLab) that is available for ICDP drilling projects. The need to minimise and quantify chemical and biological contamination should be accommodated. Standard protocols for geobiological/geochemical sampling have been established (Kallmeyer et al., 2006; Kieft et al., 2007; Kieft, 2010). Drilling fluids and drill string lubricants should be selected with an eye to avoiding organic compounds that can promote microbial growth or that can be confused with chemical biosignatures. Quantification of contamination is usually accomplished by adding solute and particulate tracers to the drilling fluid. These changes add only modestly to drilling complexity and cost but require adop-

tion early in the planning process. Drilling into hard rock, as is done for many ICDP projects, adds further challenges. Examination of core fractures may give clues to microbially mediated precipitation or dissolution of minerals. A rock splitter can be used to sub-sample the cores. Hard rock boreholes also offer the opportunity for long-term groundwater sampling, in-situ experimentation (e.g., push–pull experiments, mineral surface colonisation, etc.), and for deployment of downhole instrumentation. Installation of packers enables collection of fracture water from discrete depth intervals. In most cases, these add-on technologies are compatible with drilling for geophysical studies, but early planning is required.

Recommendations

With the rapidly increasing utilisation of the subsurface, either for exploitation of natural resources (hydrocarbons, water, heat) or long-term storage of waste products (CO_2, nuclear waste), it is of paramount importance to understand this so-far understudied environment. Over the last two decades, new findings have shown that microbes mediate many processes that were previously considered as abiotic. IODP studies in the marine realm have been the driving factor in studying the subsurface biosphere, whereas the terrestrial geomicrobiological community associated with ICDP is lagging behind, despite the great societal and scientific need to explore the terrestrial subsurface biosphere. The main reason for this is the much lower visibility and connectedness of the terrestrial deep biosphere community. It is therefore of utmost importance that the community raises its visibility and makes the broader geomicrobiology community aware of upcoming ICDP workshops and projects. Given the special requirements for contamination control and on-site sample processing, the addition of a geomicrobiological component is not always appreciated by all members of a science party. However, accurate assessment of the contamination of the core by drilling fluids is important for other disciplines as well. In order to make geomicrobiology an integral part of many future ICDP projects it is necessary to get involved in projects at an early stage and to initiate projects as well. Only through consolidated community effort can deep terrestrial biosphere research be made an integral part of ICDP.

References

Bräuer, K., H. Kämpf, E. Faber, U. Koch, H.-M. Nitzche, and G. Strauch. 2005. Seismically triggered microbial methane production relating to the Vogtland —NW Bohemia earthquake swarm period 2000, Central Europe. Geochemical Journal 39: 441–450.

Chivian D, Brodie EL, Alm EJ, Culley DE, Dehal PS, DeSantis TZ, Gihring TM, Lapidus A, Lin L-H, Lowry, SR, Moser DP, Richardson PM, Southam G, Wanger G, Pratt LM, Andersen GL, Hazen TC, Brockman FJ, Arkin AP, Onstott TC (2008) Environmental genomics reveals a single-species ecosystem deep within earth. Science 322:275–278

Colwell, F. S., T. Nunoura, M. E. Delwiche, S. Boyd, R. Bolton, D. Reed, K. Takai, R. M. Lehman, K. Horikoshi, D. A. Elias, and T. J. Phelps. 2005. Evidence of minimal methanogenic numbers and activity in sediments collected from the JAPEX / JNOC / GSC et al. Mallik 5L-38 gas hydrate production research well. In (S. R. Dallimore and T. S. Collett, eds.), Scientific Results from the Mallik 2002 Gas Hydrate Production Research Well Programme, Mackenzie Delta, Northwest Territories, Canada, Geological Survey of Canada, Bulletin 585, 11 p.

Glombitza, C., Stockhecke, M., Schubert, C. J., Vetter, A., Kallmeyer, J., 2013. Sulfate reduction controlled by organic matter availability in deep sediment cores from the saline, alkaline Lake Van (Eastern Anatolia, Turkey). Frontiers in Microbiology 4.

Gohn, G. S., Koeberl, C., Miller, K. G., Reimold, W. U., Browning, J. V., Cockell, C. S., Horton, J. W., Jr., Kenkmann, T., Kulpecz, A. A., Powars, D. S., Sanford, W. E., and Voytek, M. A. (2008) Deep drilling of the Chesapeake Bay impact structure. Science 320:1740–1745.

Horsfield, B., H. J. Schenk, K. Zink, R. Ondrak, V. Dieckmann, J. Kallmeyer, K. Mangelsdorf, R. di Primio, H. Wilkes, R. J. Parkes, J. Fry, B. Cragg (2006) Living microbial ecosystems within the active zone of catagenesis: Implications for feeding the deep biosphere. Earth and Planetary Science Letters, 246, 55–69

Horsfield, B., Kieft, T. L., Amann, H., Franks, S. G., Kallmeyer, J., Mangelsdorf, K., Parkes, R. J., Wagner, D., Wilkes, H., Zink, K.-G. 2007.

Jørgensen, B. B. (2012) Shrinking majority of the deep biosphere. Proceedings of the National Academy of Sciences 109, 15976–15977.

Kallmeyer, J., Mangelsdorf, K., Cragg, B. A., Parkes, R. J., and Horsfield, B., 2006. Techniques for contamination assessment during drilling for terrestrial subsurface sediments. Geomicrobiol. J., 23:227–239, doi:10.1080 / 014904506007 24258.

Kallmeyer, J., Pockalny, R., Adhikari, R. R., Smith, D. C. and D'Hondt, S. (2012) Global distribution of microbial abundance and biomass in subseafloor sediment. Proceedings of the National Academy of Sciences of the United States of America 109, 16213–16216.

Kieft, T. L., Phelps, T. J., and J. K. Fredrickson. 2007. Drilling, coring, and sampling subsurface environments. pp. 799–817, In: Manual of Environmental Microbiology, Third Edition. Hurst, C. J. (Ed.), ASM Press, Washington, DC.

Kieft, T. L. 2010. Sampling the deep sub-surface using drilling and coring techniques. pp. 3427–3441, In: Microbiology of Hydrocarbons and Lipids. K. N. Timmis (Ed.), Springer Verlag, Berlin.

Mangelsdorf, K., J. Kallmeyer. 2010. Integration of deep biosphere research into the International Continental Scientific Drilling Programme. Scientific Drilling 10: 46–55.

Onstott, T. C., T. J. Phelps, F. S. Colwell, D. Ringelberg, D. C. White, D. R. Boone, J. P. McKinley, T. O. Stevens, P. E. Long, D. L. Balkwill, T. Griffin, and T. Kieft. 1998. Observations pertaining to the origin and ecology of microorganisms recovered from the deep subsurface of Taylorsville Basin, Virginia. Geomicrobiology Journal 15:353–385.

Sleep, N. H., M. D. Zoback. 2007. Did earthquakes keep the early crust habitable? Astrobiology 7:1023–1032.

The GeoBiosphere. pp. 163–211. In: U. Harms, C. Koeberl and M. D. Zoback (Eds.) Continental Scientific Drilling. A Decade of Progress, and Challenges for the Future. Springer Verlag, Berlin.

Vuillemin, A., Ariztegui, D., 2013. Geomicrobiological investigations in subsaline maar lake sediments over the last 1500 years. Quaternary Science Reviews 71, 119–130.

Wilhelms, A., S. R. Larter, I. Head, P. Farrimond, R. di-Primio, C. Zwach. 2001. Biodegradation of oil in uplifted basins prevented by deep-burial sterilisation. Nature 411:1034–1037.

Zink, K. G., H. Wilkes, U. Disko, M. Elvert and B. Horsfield (2003). 'Intact phospholipids—microbial 'life markers' in marine deep subsurface sediments.' Organic Geochemistry 34(6): 755–769.

Zoback, M. D., Emmermann R. (eds) 1994. Scientific rationale for the Establishment of an International Programme of Continental Scientific Drilling, Potsdam, International Lithosphere programme, Coordinated Committee Continental Drilling (CC4) 150 pp.

CATACLYSMIC EVENTS— IMPACT CRATERS AND PROCESSES

Christian Koeberl Department of Lithospheric Research, University of Vienna, Austria
Philippe Claeys Earth System Science, Vrije Universiteit Brussel, Belgium

Figure 33. The Ouarkziz impact crater, northwestern Algeria, formed by a meteor impact less than 70 million years ago.

Lay of the land

On February 15, 2013, a brilliant fireball was observed over the southern Ural region (Russia), followed by an explosion and shock wave that damaged several buildings and injured more than a thousand people in the region.

Interplanetary collisions recorded in meteorites and the ubiquitous presence of impact craters on solid planetary surfaces demonstrated that since the origin of the solar system cratering constitutes a fundamental geological process. On Earth, more than 30 years of Cretaceous–Paleogene (K–Pg) debates led to a new paradigm in geology by demonstrating that biological evolution is not only influenced by superficial or internal geological processes, but also by punctual, external, highly energetic events. Currently, of the 184 known terrestrial impact craters about one third are not exposed on the surface and can only be studied by geophysics or drilling. In addition, even exposed craters require drill cores to obtain deeply buried impactite lithologies, to provide ground-truth for geophysical studies or models, and to gain a 3D view of the interior of the structure. Considering that since Hadean times collisions have shaped terrestrial planets and that some impact events demonstrably affected the geological and biological evolution on Earth, the formation and understanding of impact structures are of interest not only to earth scientists, but also to society in general.

Past accomplishments in ICDP

Several **meteorite impact structures** have been drilled in ICDP projects (e.g., Chicxulub, El'gygytgyn, Lake Bosumtwi, Chesapeake Bay). Meteorite impact studies in ICDP projects have contributed considerably to the heat and mass transfer and hydrothermal processes of impact processes (see earlier chapter on Heat and Mass Transfer), and provided means to test the prevailing theories of impacts (Poag et al., 2004; Abramov and Kring, 2007; Zurcher and Kring, 2004, Schulte et al., 2010; Balburg et al., 2010; Ferriere et al., 2008; Sanford, 2005). In addition, the deep holes have given useful opportunities to study the present thermal regime and hydrogeology of impact structures and the thermal and hydraulic properties of shock metamorphic rocks (Willhelm et al. 2004, 2005; Popov et al., 2004; Mayr et al. 2008; Čermak et al., 2009; Šafanda et al, 2005, 2009; Gondwe et al., 2010; Maharaj et al., 2013; Sanford et al., 2013).

Chicxulub (Mexico): The Chicxulub crater at the tip of the Yucatán Peninsula (México), is the world's third largest known impact structure and is widely accepted to have been responsible for the dramatic environmental changes at the K/Pg boundary. The CSDP (Chicxulub Scientific Drilling Project) borehole Yaxcopoil-1 (Yax-1) was drilled from December 2001 through March 2002 and extended to a depth of 1510 m. Integration of the Yax-1 drill results with the existing geophysical and borehole database led to a revised crustal model for the multi-ring Chicxulub structure (Morgan et al. 2005). The main CSDP results were published in two special issues of the journal *Meteoritics and Planetary Science* in June and July 2004 (Urrutia-Fucugauchi et al., 2004).

Bosumtwi (Ghana): The 11 km diametre, 1.1 Ma Bosumtwi impact crater in Ghana is arguably the best-preserved complex young impact structure. It displays a pronounced rim, and is almost completely filled by Lake Bosumtwi, a hydrologically closed basin, in which an approximately one-million-year continuous finely laminated sedimentary sequence was deposited. Within the framework of an international multidisciplinary ICDP-led drilling project, 16 drill-cores were obtained at six locations, using the GLAD-800 lake-drilling system, from June to October 2004. The 14 sediment cores were investigated for paleoenvironmental indicators. The two impactite cores, LB-07A and LB-08A drilled into the deepest section of the annular moat (540 m) and the flank of the central uplift (450 m), respectively are the main subject of a special issue of the journal Meteoritics and Planetary Science (see Koeberl et al., 2007).

Chesapeake Bay (USA): The Late Eocene Chesapeake Bay impact structure lies buried at moderate depths below Chesapeake Bay in Southeastern Virginia, USA. It inviting target for ICDP drilling because of the location of the impact on the Eocene continental shelf, its three-layer target structure, its large size (about 85 km diametre), its status as the source of the North American tektite strewn field, its temporal association with other late Eocene terrestrial impacts, its documented effects

on the regional groundwater system, and its previously unstudied effects on the deep microbial biosphere. Details about this project can be found in, e.g., Gohn et al. (2008, 2009).

El'gygytgyn (Russia): The El'gygytgyn impact structure in Chukutka, Arctic Russia, is the only terrestrial impact crater currently formed in mostly acid volcanic rocks. In addition, it has provided an excellent sediment trap that records paleoclimatic information for the 3.6 million years since its formation. For these two main reasons, because of the importance for impact and paleoclimate research, El'gygytgyn was the subject of an ICDP drilling project in 2008 and 2009. Recently, results from the impact aspects of the project have been published in a special issue of the journal Meteoritics and Planetary Science (Koeberl et al., 2013).

Further impact-related projects are the 2007 FAR-DEEP and the 2011–12 Barberton drillings.

Fundamental open questions

The following list singles out a number of aspects of impact cratering and their effects on the global earth system that can be investigated with impact crater drilling.

1) Obtain ground truth for confirmation of origin of structures (not without other objectives).

2) Understand the role of target rock types ranging from crystalline to sedimentary rocks and address the effect of water and volatiles in target strata.

3) Understand the different phases of the cratering process, and in particular a) the excavation of the transient cavity, its geometry and the reaction of different types the target lithologies (ex. volatile-rich vs dry silicates) as they are traversed by the shock waves originating from the impact point, b) the formation of the central-peak, peak-ring or for the largest structures, multi-rings that result, as the pressure is released, from the uplift of the compressed deep lithologies, and their subsequent collapse at the end of the cratering process.

4) Document the final modification of the crater by margin collapse, the behaviour of mega-blocks, and the evolution of bounding fault geometries at depth—merging into a decollement or some type of distributed brittle deformation.

5) Understand the formation, emplacement and magmatic evolution of melt-sheets and their relationships at depth to the underlying shocked/fractured basement.

6) Complement numerical modelling through a better understanding of the interior of impact structures, i.e., the distribution and types of impactites generated in different target environments, the incorporation of a meteoritic components in the melt phases, differentiate fall-back from fall-out suevites, track the spatial decay of shock effects and rock damage, estimate the total energy released etc.

7) Find evidence in the micro- to macro-scale for the transient loss of strength in crater material to verify models such as acoustic fluidisation.

8) Link ejecta and source crater to document the transport, dispersal and deposition of the material throw out of the crater and its timing according to different processes distributed locally around the structure or in some case globally.

9) Constrain the role of crater size, composition of target and energy transfer from the cratering process to the global Earth system and the effects of large, catastrophic impact events on the environment and the biosphere including cause-effect relationships for mass extinctions.

10) Understand the chemical and physical processes during vapour, melt and dust interaction with atmosphere.

11) Utilization of impact structures for paleo-climatic/environmental investigations, and to understand the formation associated resources (oil & gas, ore mineralization).

12) Understand the time-dependant effects during the formation of large impact melt complexes during differentiation and post-impact hydrothermal activities.

Future scientific targets

Specific Suggestions for Future Impact-Related Drilling Projects Future ICDP drillings of impact sites should focus on contributing to solve fundamental questions of impact cratering. The priority should not be to focus on specific characteristics one particular crater. Priority has to be given to achieving a better understanding of the general processes, which form the crater and lead to regional and global geological, environmental and biological effects. Future scientific drilling projects must include and interpret all available geoscience data (from drill core to remote sensing). Finally, these drilling projects should be interdisciplinary (see Bosumtwi for example) and focused on world-class geological sites and stimulate collaboration with other international organizations (e.g., IODP) or industry (Ex. Mjølnir). At the same time, impact-related scientific drilling should integrate as much as possible state-of-the-art research efforts into biological, paleo-climate, resources and socio-economic aspects of impact craters.

Sudbury, Canada: The Sudbury Structure (Canada) offers the only example of a basin-sized (250 km diameter) impact structure on Earth that can be examined at a range of stratigraphic levels from the shocked basement rocks of the original crater floor up through the impact melt sheet and on through the fallback material and the crater-filling sedimentary sequence. It hosts one of the world's largest concentrations of magmatic Ni-Cu-Pt-Pd-Au mineralization, which formation mechanisms still require clarifications. Sudbury is the premier locality on Earth to study processes related to impact and planetary accretion, as well as a wide range of magmatic differentiation including the generation of

Figure 34. Outcrop of Vrederfort Impact Crater rocks in South Africa

large magmatic sulfide deposits through scientific drilling. An international workshop funded by ICDP was held at Sudbury in September 2003 to review current geological, geophysical and geotechnical studies and results from existing exploration drilling efforts to formulate a full proposal to ICDP.

Chicxulub, Yucatan, Mexico: Because of its size and importance, the Chicxulub structure certainly requires more drilling to understand its formation, visualize its internal 3D morphology and ultimately how it so drastically affected the biosphere. A deep drilling within the central peak-ring would reach the thick melt-sheet surmised by geophysical studies and perhaps, barely penetrated by the old Pemex oil exploration well Chicxulub 1 at about 1580 m below sea level. Understanding the formation, differentiation and emplacement of this melt would constitute major advances in our current understanding of crater formation, and magma evolution in general. On Early Earth, similar impact related vast melt-sheet likely played a role in the formation of the first crust, and comparable processes must have occurred on differentiated asteroid such as Vesta. Moreover, in analogy with Sudbury, ore mineralization could be associated with the evolution of this melt-sheet. Further down from the melt-sheet, drilling at such location would also eventually reach deep crustal lithologies brought up during the uplift of the central peak ring. Another option is a sequence of shallow drillings outside the crater to document the emplacement of the thick ejecta blanket that extend over >300 km from the rim. This project would characterize the type and proportion of deep-crater rocks entrained within the ejecta blanket and transported over large geographic areas, as part of fast-moving turbulent cloud of vapor, molten and solid particles.

Drilling issues

The approximately 184 recognized impact structures on Earth ranging in size from ~300 km to a few tens of meters in diameter are classified into three types: simple craters (e.g., Meteor Crater), complex craters (e.g., Bosumtwi, Chesapeake Bay), and multi-ring basins (e.g., Chicxulub, Vredefort). Each crater morphology-type implies different formation processes controlled essentially by the energy release and the composition of the target lithologies.

Our current understanding, as revealed by direct examination of the subsurface character of terrestrial impacts and their deposits is limited, in most cases, to data from a single drill hole. Such single drill hole represents, for a 50 km diameter structure, 1×10^{-10} % of the area or 1×10^{-4} % of the diameter. There are no cores, which extend through or deeply into the central uplift or the floor deposits (allochthonous and autochthonous fragmental material with and without melt or the melt sheet) or the bounding faults of complex craters. No cores have been obtained into the walls of craters or sufficiently deep through the floor, and away from the rim, to examine the manner in which the shock effects are attenuated with distance.

The center of complex impact craters typically has a central uplift. There, rocks are raised from significant depth below the crater and remain at shallow levels after the impact. Within the central uplift, lithologies that were originally at greater depth are exposed, allowing access by means of drilling, in large structures, to lower crustal rocks that would otherwise not be accessible through other geological processes, such as tectonic or mountain building.

Impact craters can produce relatively long-lived hydrothermal systems. The studies of such systems have application to commercial mineralization, hydrothermal alteration processes, and extremophile habitats. Some impact structures are associated with significant economic deposits. Sudbury (Canada) hosts Ni-Cu-Pt minerals. The Cantarell oil field in Mexico, the world's 8th largest, is associated with the Chixculub structure. Impact structures in the Williston Basin (US/Canada), Ames (Oklahoma), Avak (Alaska), etc., are important hydrocarbon reservoirs.

Ages of impact events are poorly known and can only be directly determined by analysis of melted material produced by the impact, both in terms of radiometric ages and biostratigraphic ages. Age data provide insight into the cratering rate on Earth and the correlation of impact events to terrestrial extinctions and the possibility of periodic increases in the crater rate. While there is a clear temporal association between the K/Pg boundary and its extinction and the Chicxulub impact, the specific causality mechanism of the impact has not yet been defined. Additional drilling at the Chicxulub impact could shed light on the target materials and the manner in which they were altered by the impact and modified the global environment. A particularly relevant question with respect to impact-extinction correlations regards differences in the target rocks and how alteration of that material changes the atmosphere composition and atmospheric thermal regime.

Science targets at impact structures and considerations for the future:

- Does a unique geological, geochemical and geophysical signature exist for large terrestrial craters?
- Will we be able to identify (fingerprint) the 'remnants of early Earth impacts' in Archean crustal blocks?
- Do we overestimate the melt volume production in small to midsize craters?
- This has consequences for the cooling history of craters (such as the existence/longevity of post-impact hydrothermal activity in impact craters, mineral deposits, etc.)
- Impact crater research offers a special opportunity to establish a better link between absolute age determinations (dating) and paleontological time scales.
- We need to study more craters to get a better handle on the role of geological setting (sediment versus hard-rock environments, rheological models for high pressure and temperatures (can we do better than acoustic fluidization models?), do we know the equation(s) of state for realistic (complex) geological target rocks (including water saturated sediments)?).

- Drilling outside an impact crater may provide us with another set of geological markers (such as tektites in the sedimentary column), and in the immediate vicinity of craters we may obtain information about shock deformation, the mobility of impact melts and cooling history.
- Establish 'typical crater structure' for complex craters on Earth, and how they evolve from one morphological type to another with increasing crater size.
- Refine the ages of the majority of impact craters, as only 18 of the 184 craters are dated with a precision of 2% (Jourdan et al. 2013). Precision dating is capital to understand the relationships between impact and environmental evolution as well as answering planetary scale questions regarding frequency of impact, crater clusters, asteroid or comet showers, etc.
- Determine the nature of a topographic peak ring.
- Determine the effect of target lithology and target layering on crater formation.
- How does obliquity of impact affect the total size of the crater formed and the environmental effect of the impact (experiments and numerical models give very different answers to this)?
- Can we determine the direction and angle of impact from the ejecta deposits?
- How serious is the threat of a large impact today?
- What causes the weakening that allows crater collapse —thermal softening, acoustic fluidization, or something else?
- What is the nature of rings in multi-ring basins?
- How is the melt volume and melt distribution related to the target rheology (porosity, sediments versus crystalline) and impactor type and velocity?

Recommendations

Scientific drilling of large craters provides essential petrological, structural, geochronological, and geophysical data, allowing a quantum leap forward in our understanding of the evolution of large impact structures and the physical, chemical and biological processes that have operated within these craters over time. Links to other important topics in continental drilling (such as fault studies, palaeoclimate, human origins, deep biosphere, natural resources) allow for joint projects. The determination of the energy relationships of impacts, their effects on the environment, and the impact hazard assessment provide essential socio-economic reasons to use drilling in the study of impact processes on the Earth.

References

Abramov, O. and Kring, D. A., 2007. Numerical modeling of impact-induced hydrothermal activity at the Chicxulub crater. Meteoritics & Planetary Science 42, 93–112.

Gohn G. S., Koeberl C., Miller K. G., and Reimold W. U. (eds.) (2009) The ICDP–USGS Deep Drilling Project in the Chesapeake Bay Impact Structure: Results from the Eyreville Core Holes. Geological Society of America, Special Paper 458, 975 pp

Gohn G. S., Koeberl C., Miller K. G., Reimold W. U., Browning J. V., Cockell C. S., Horton J. W., Kenkmann T., Kulpecz A. A., Powars D. S., Sanford W. E., and Voytek M. A. (2008) Deep drilling into the Chesapeake Bay impact structure. Science 320, 1740–1745.

Jourdan, F., Reimold, W. U., and Deutsch, A. (2012). Dating terrestrial impact structures. Elements 8(1), 49–53. doi:10.2113/gselements.8.1.4

Koeberl C. and Milkereit B. (2007) Continental drilling and the study of impact craters and processes —an ICDP perspective. In: Continental Scientific Drilling (eds. Harms, U., Koeberl, C., and Zoback, M. D.), Springer, Heidelberg, p. 95–161.

Koeberl C., Milkereit B., Overpeck J. T., Scholz C. A., Amoako P. Y. O., Boamah D., Danuor S. K., Karp T., Kueck J., Hecky R. E., King J., and Peck J. A. (2007) An international and multidisciplinary drilling project into a young complex impact structure: The 2004 ICDP Bosumtwi impact crater, Ghana, drilling project —An overview. Meteoritics and Planetary Science 42, 483–511.

Koeberl C., Pittarello L., Reimold W. U., Raschke U., Brigham-Grette J., Melles M., and Minyuk P. (2013) El'gygytgyn impact crater, Chukotka, Arctic Russia: Impact cratering aspects of the 2009 ICDP drilling project. Meteoritics and Planetary Science 48, 1108–1129.

Mayr, S. I.; Burkhardt, H.; Popov, Yu.; Wittmann, A. (2008): Estimation of hydraulic permeability considering the micro morphology of rocks of the borehole YAXCOPOIL-1 (Impact crater Chicxulub, Mexico)., International Journal of Earth Sciences 97(2) 385–399

Morgan J., Warner M., Urrutia-Fucugauchi J., Gulick S., Christeson G., Barton P., Rebolledo-Vieyra M., and Melosh J. (2005) Chicxulub crater seismic survey prepares way for future drilling. EOS Transactions of the American Geophysical Union 86: 325–328

Poag, C. W.; Koeberl, C.; Reimold, W. U. (2004): The Chesapeake Bay Crater., Springer-Verlag, New York 522pp

Popov, Y.; Romushkevich, R.; Bayuk, I.; Korobkov, D.; Mayr, S.; Burkhardt, H.; Wilhelm, H. (2004): Physical properties of rocks from the upper part of the Yaxcopoil-1 drill hole, Chicxulub crater., Meteoritics and Planetary Science 39(6) 799–812

Sanford, W. E. (2005): A simulation of the hydrothermal response to the Chesapeake Bay bolide impact., Geofluids 5 185–201

Sanford, W. E.; Doughten, M. W.; Coplen, T. B.; Hunt, A. G.; Bullen, T. D. (2013): Evidence for high salinity of Early Cretaceous sea water from the Chesapeake Bay crater., 10.1038/nature12714 nature letter

Schulte P.; Alegret L.; Arenillas I.; Arz J. A.; Barton P. J.; Bown P. R.; Bralower T. J.; Christeson G. L.; Claeys P.; Cockell C. S.; Collins G. S.; Deutsch A.; Goldin T. J.; Goto K.; Grajales-Nishimura J. M.; Grieve R. A.; Gulick S. P.; Johnson K. R.; Kiessling W.; Koeberl C.; Kring D. A.; MacLeod K. G.; Matsui T.; Melosh J.; Montanari A.; Morgan J. V.; Neal C. R.; Nichols D. J.; Norris R .D.; Pierazzo E.; Ravizza G.; Rebolledo-Vieyra M.; Reimold W. U.; Robin E.; Salge T.; Speijer R. P.; Sweet A. R.; Urrutia-Fucugauchi J.; Vajda V.; Whalen M. T.; Willumsen P. S. (2010): The Chicxulub asteroid impact and mass extinction at the Cretaceous–Palaeogene boundary., Science, ISSN:1095–9203 327 1214–1218.

Urrutia-Fucugauchi J., Morgan J., Stöffler D., and Claeys P. (2004) The Chicxulub Scientific Drilling Project (CSDP). Meteoritics and Planetary Science 39, 787–790.

Wilhelm, H.; Popov, Y.; Burkhardt, H.; Safanda, J.; Cermak, V.; Heidinger, P.; Korobkov, D.; (...), Mayr, S. (2005): Heterogeneity effects in thermal borehole measurements in the Chicxulub impact crater., Journal of Geophysics and Engineering 2(4) 357–363.

Zurcher, L.; Kring, D. A. (2004): Post-impact hydrothermal alteration in the Yaxcopoil-1 hole, Chicxulub impact structure, Mexico. Meteoritics and Planetary Science 39(7) 1199–1221.

LINKS WITH OTHER ORGANISATIONS— TOWARDS A MORE INTEGRATED APPROACH TO SCIENTIFIC EARTH DRILLING

Ulrich Harms GFZ—German Research Centre for Geosciences, Germany
Keir Becker Rosenstiel School of Marine & Atmospheric Science, University of Miami, Miami, USA

International scientific drilling has developed over the past five decades in the marine, continental, and Antarctic realms, culminating in the current international programmes IODP, ICDP, ANDRILL and others. While there is a wide overlap in the overarching scientific objectives of these programmes, their structures and organisations have remained independent and with significant differences. On the one hand, there are technical differences in the various tools deployed in operations on long-term chartered drilling vessels versus short-term contracted land drilling rigs of opportunity, but there has also been important engineering cooperation such as the sharing of hydraulic piston coring designs between ODP/IODP and ICDP/DOSECC. More importantly, there have been significant differences in funding models, from full programme funding over several years (ODP/IODP) to partial support of single projects (ICDP), and this has led to important differences in the way projects are proposed, evaluated, and supported.

Recently, several projects addressed research themes that cross shorelines ('amphibious projects') and require participation by more than one programme. However, to date these joint proposals have been independently proposed, reviewed, and nurtured until approved or rejected. Important cross-programme issues and opportunities were addressed at a December 2011 ICDP/IODP Task Force meeting, but implementing any recommendations from that meeting was suspended pending renewal and reorganisation of IODP. The reorganisation of the post-2013 IODP in three branches with more independent funding and decision-making, as well as preparation of the new science plan for ICDP (this White Paper), have provided the best opportunity to date to increase the level of cooperation and coordination among programmes. Shortly after the ICDP Science Conference (November 2013) both programmes agreed on a joint call for new proposals with focus on land–sea transects. These united proposals will be reviewed and decided on by coordinated panel actions and will be funded and executed together.

A number of accompanying joint actions should be considered to support these goals:

1) The programmes should ensure that coupled and joint proposals are reviewed and nurtured in a coordinated approach to ensure cooperatively funding and timing. The pragmatic way forward is to harmonise review panel meeting dates and venues for joint discussion and decision.

2) This Science Plan has taken the IODP Science Plan into account and the inter-

AMPHIBIOUS SCIENTIFIC DRILLING

Achim Kopf Center for Marine Environmental Sciences, Bremen University, Bremen, Germany

At times of global change and increasing urbanisation of coastal areas, the well-being of its populations represents one of the major challenges for society. The UN Environmental Panel notes an increase in the number of natural hazard events per year over the past 100 years. A particularly good example is the Ligurian coast, France. The most recent event was the 1979 Nice Airport landslide, which caused a tsunami, numerous casualties, and severe damage to the capital and infrastructure along this part of the French Riviera.

In slope failure processes, fluids play a major role since the water and gas between the particles lower cohesive strength and favour disaggregation and slip. Causes for enhanced fluid flow and overpressure in the underground include precipitation, groundwater charging, earthquake shaking, formation of microbial gas, dissociation of gas hydrate, sediment deformation and human activity, to name just a few. Still, the exact nature of onshore and offshore landslides is incompletely understood so that scientific drilling and borehole monitoring is essential. Only an amphibious approach can set up an appropriate network of observation points to allow researchers a comprehensive landslide understanding and hazard assessment. Boreholes on land will help characterising the inputs and discharge rates of fluids as well as the permeability and strength of the sediment or rock in the aquifer system. Offshore boreholes will then serve to monitor how sediment properties and fluid flow change as a function of the inputs. Borehole instruments are capable of unambiguously identifying landslide triggers, allow hole-to-hole experiments and correlations, and may also function as early-warning systems in case a real-time data transfer is realised.

Affordable drilling onshore and offshore by utilising mission-specific drilling platforms is the only means to thoroughly study phenomena such as coastal geohazards, which represent a global societal threat and challenging scientific endeavour. ICDP and IODP are working closely together to streamline their respective procedures so that amphibious projects like this one can come to fruition.

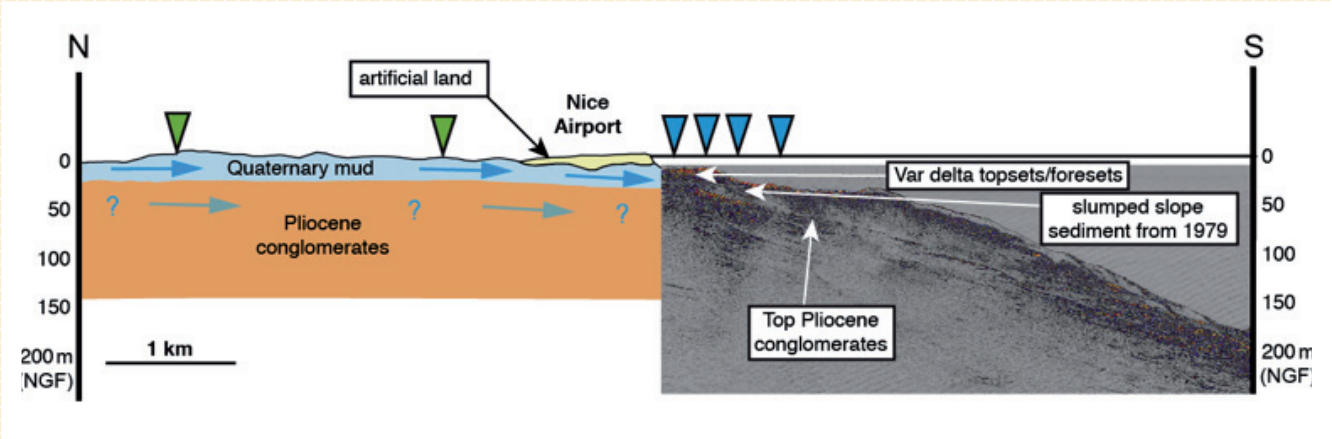


Figure 35. The effects of the 1979 tsunami in the village of Antibes

Figure 36. Composite cross-section of the Ligurian amphibious drilling profile, combining geological information onshore with marine seismic profiles. Black vertical lines indicate locations of existing groundwater wells. Triangles represent the (sometimes projected) sites proposed for amphibic scientific drilling (Green = ICDP, blue = IODP). Marine seismic reflection profile with the top of the Pliocene conglomerates underlying the slumped as well as deltaic sediments composed of permeable Holocene sand interbedded with clay. Blue arrows mark Var river discharge and groundwater flow in Quaternary and Pliocene (?) units.

national drilling programmes should then cooperate to identify high priority science themes for future joint approaches. Toward this end, joint thematic workshops should be further developed and the programmes should cooperate on unified calls for proposals (e.g., in EOS and on the internet) for land-sea-transect projects.

3) Common outreach can be greatly improved through better linking of websites.

4) The programmes should consider modifying and eventually unifying programme support offices for proposal support and nurturing.

Finally, the research infrastructure available in ICDP and IODP, such as the mobile components used in ECORD operations, should be further integrated, and technology such as drilling, logging, sample storage and data curation should be shared more closely.

Although it is premature to consider full integration of international scientific drilling programmes, there is an obvious need for streamlining. There is a strong core of nations providing funding to IODP and ICDP, and many already handle this support through a single national programme. Accordingly, potential synergies must be utilised and a concerted approach to use drilling to answer critical question for earth science will be the way forward. An overarching parent organisation with independent but nevertheless fully coordinated organisations is a pragmatic way forward.

A number of scientific themes have already been identified for closer collaboration between ICDP and IODP. These include investigations at continental margins, large igneous provinces, ophiolite belts, and major plate boundary faults. In addition, combined technological projects make good sense across the land–sea boundary. These include sea-level studies, investigations of permafrost across continental margins, and investigations of active fault processes at plate boundaries as a result of the progressive build-up and release of tectonic stress and strain.

The latter is particularly topical at present. IODP has undertaken a decadal programme of drilling and observatory installation to understand the controls on large 'megathrust' quakes (M>8) that occur offshore and threaten areas such as Japan and Central America. Earthquakes in tectonic zones inside continents result in significant disasters and have been targeted by ICDP. The first efforts at drilling into active fault systems by ICDP and IODP were groundbreaking and fraught with technical challenges. ICDP is now drilling into a fault system in the Sea of Marmara, in Turkey, and on the Alpine Fault in New Zealand. Better characterisation of fault-zone behaviour will allow development of predictive capabilities and ultimately help to save lives through better definition of hazardous zones and tighter regulation of construction practices. Fault-zone observatories must have onshore to offshore links and must be integrated with regional programmes which link multiple geophysical and geochemical sensor systems.

Figure 37. Jack up platform used in shallow waters inaccessible for drilling vessels and land drill rigs

ROLE OF INDUSTRY

Stefan Luthi Applied Geology, Delft University of Technology, Delft, Netherlands
Nick Arndt Institut des Sciences de la Terre, Université de Grenoble, Saint-Martin d'Hères, France

Figure 38. 'Columbia Protecting Science and Industry' by sculptor Caspar Buberl above the main entrance on the north side of the Arts and Industries Building (Smithsonian museum) in Washington, D.C.

From a societal, technological and financial point of view it would be highly desirable for ICDP to have closer links with industry. This occurs now primarily in the form of contractor–client relationships whereas ICDP and industry would both benefit substantially from a relationship based on scientific and technological collaboration on a mutual and balanced give-and-take partnership. Potential industry partners include companies in upstream oil and gas, mining and the geotechnical, geoengineering and geothermal domains. An interesting target group are major technology providers such as oil service companies, semi-national and national research organisations, and oil and gas companies who often operate under government guidelines that require significant in-house and outsourced R&D investments.

Several forms of collaboration or partnership can be envisioned, such as full ICDP membership, project-based collaboration or technological development contracts. Over the years ICDP has enjoyed fruitful collaboration at the project level—such as the IDDP project on Iceland and the Songliao Basin project in China. Also, to aid in technol-

ogy transfer in the field of drilling logistics, an industry partner has served on its Executive Committee and was an official sponsor of ICDP. While experience at our sister organisation IODP has recently indicated that the large exploration and production (E&P) companies would prefer collaboration on a case-by-case project level basis, other potential partners might be open for full membership. Specifically, some national or semi-national E&P companies might be open for membership in order to provide access for their national researchers to ICDP projects and at the same benefit from new scientific and technological developments.

The petroleum, natural gas, and mining industries are constantly drilling exploration and production wells, and so tremendous potential exists for addressing scientific questions with these same boreholes. Project-based participation can be in the form of piggy-backing onto planned projects, through data exchange, or simply for PR purposes in a particular country or for a specific research goal. This is already ongoing in several ICDP projects and can be further enhanced and encouraged on both sides. A very promising area of industry involvement lies in technological development, where ICDP sees great potential in collaborating on issues such as high-pressure/high-temperature measurement logs, fluid and biological sampling tools, permanent downhole monitoring and more. ICDP will consider the development of databases as a means of developing and maintaining industry contacts as well improving and streamlining communication with key industry contacts.

ICDP is a science driven organisation; the notion that industry membership would change all that is unfounded. Symbiotic, transparently regulated and operated cooperation on a science and technology level makes good sense.

EDUCATION AND OUTREACH

Thomas Wiersberg GFZ — German Research Centre for Geosciences, Germany

Scientific drilling has strong added value in that it addresses the fundamental challenges facing mankind in the twenty-first century, namely sustainable resources, environmental changes and natural hazards. It is extremely important that the general public, funding bodies and politicians alike are made aware of that fact because drilling projects are mainly financed using taxpayers' money. Focused knowledge transfer, education and outreach must be made visible to the public, to media and decision makers at all levels. Recent discussions about the exploitation of unconventional gas resources, carbon capture and storage and geothermal energy have brought deep drilling into the public eye, and unfortunately often with a negative connotation. The backlash affects all who are concerned with the science and technology of the geological subsurface, be it for pure or applied purposes. Enhanced education and outreach is needed at ICDP to bring across an understanding of geoscience and the benefits of scientific drilling; it must be an integral part of every project from early on.

Training

Drilling is the ultimate method to retrieve matter from and yield information about the Earth's interior structure, processes and evolution, but unfortunately drilling is not taught at most earth science faculties of universities worldwide. Therefore an important component of the ICDP is training of earth scientists, engineers, and technicians in drilling-related know-how and technologies. ICDP offers a suite of different training measures, including annual training courses and, on request specific training courses on e.g. geophysical downhole logging, ICDP's Drilling Information System DIS and ICDP's Online Gas Monitoring System OLGA. Principal Investigators can inquire ICDP Training measures even at their drill site.

Principal investigators are overwhelmed by the complexity of planning a scientific project as they are not that familiar with drilling engineering or project controlling and management. To mitigate these shortcomings, a training course on project management will be implemented every second year to even have the programme benefit from.

In addition to the pure ICDP Training, ICDP will facilitate and actively assist in establishing joint training measures with geoscience partner programmes (IODP, ANDRILL), e.g. summer schools.

THE JOURNAL SCIENTIFIC DRILLING —SCIENCE IN ACTION—

Ulrich Harms GFZ—German Research Centre for Geosciences, Germany

Earth science meets drilling engineering in any scientific coring project. Communicating the technical challenges and initial scientific results requires some bridge construction as scientists tend to publish research results while engineers write technical reports but interested lay people, media and stakeholders want to hear about discoveries, sensations and records.

The journal *Scientific Drilling* addresses these needs with:

- *Scientific reports* that provide insight into research goals and first findings of a drilling campaign and describe at the same time the technical achievements, tools deployed and tests performed
- *Progress reports* that serve to publish new results of smaller projects or shares of multi-phase missions
- *Technical reports* that permit the publication of new instruments, methods or tool developments
- *Workshop reports* that assist publication of novel ideas or conclusions of thematic meetings. They also serve to call for participation in new goals.

Scientific Drilling has meanwhile been established not only as scientific publication but also as an outreach instrument for the whole scientific drilling and earth science community, the public and even for the oilfield service industry.

Another facet of the journal is its pioneering role in the cooperation between the ocean drilling realm and Earth scientists working on continents as the ICDP and Integrated Ocean Drilling Program, IODP jointly founded it in 2005. This paved the pathway for the close cooperation that is meanwhile throughout scientific drilling programs.

Figure 39. The Scientific Drilling Journal—a joint publication with IODP.

Education

A first and easy step to encourage and enthuse the next generation of scientists is to provide high school teachers with the specialised materials and courses they need. Similar to IODP's 'Teachers at the Sea' programme, ICDP will develop a programme 'Teachers at the Drill Site' to bring continental scientific drilling to the classrooms. An alternative will be to bring pupils to the facilities, e.g. core repositories or drill sites. Drill sites are landmarks that draw attention locals and people from a wider area, as one can see by the great success of the German KTB Geocenter. If not located in remote areas, ICDP drill sites shall be considered to serve as Geoparks after project completion.

Outreach

To the science community

ICDP unites a large and still growing science community of about 6000 individuals all over the world. Academics engaged in scientific drilling span very different fields of expertise, e.g. geology, biology, physics, and chemistry. Most scientists are not familiar with drilling engineering. To conduct a successful project sharing information and expertise, furthering interaction and training is therefore a must.

Town Hall meetings at international conferences inform the scientific drilling community about ongoing ICDP drilling activities. These conferences will remain excellent opportunities to make scientists aware of possible collaborations. Scientific sessions at those conferences remain also an important tool to address scientific results from recently completed or ongoing projects and to present new technical developments. Conference booths in cooperation with other programmes provide information and exhibit instruments and videos.

The journal *Scientific Drilling* (www.scientific-drilling.net) delivers peer-reviewed science reports from recently completed and ongoing international scientific drilling projects as well as reports on engineering developments, technical developments, workshops, progress reports, and includes also a short news section for updates about community developments. The journal is issued twice a year and serves as an additional outreach tool for the scientific community.

To raise awareness amongst young scientists, a better visibility of the programme on social media (Facebook, Twitter, LinkedIn) will help to raise the profile of ICDP. In addition, drilling projects are now asked to open twitter accounts, post a Facebook page, or run a blog to stay in steady contact with the community. Involvement of early career scientists in ICDP projects is often difficult due to funding issues. Funds will be raised on different levels to directly aid early career scientists, particularly doctoral students and post-doctoral fellows. Merit-based awards for outstanding young researchers will be established for grant, tuition, research costs, and travel. Moreover, workshop proposals will become 'open access' and are posted as an event on the ICDP website

THE VALUE OF ON-SITE TRAINING

Thomas Wiersberg GFZ—German Research Centre for Geosciences, Germany

Drilling develops more and more to an important and powerful tool in geosciences, but unfortunately drilling will not be taught in geoscientific faculties of the universities world wide. Therefore an important component of ICDP is the capability to train earth scientists, engineers, and technicians. ICDP training includes annual courses and, on request, theme-specific training e.g. on data management, downhole logging, or gas monitoring.

The idea of the annual ICDP training courses is to teach fundamentals about drilling-related technologies and methods, but just as important is to introduce the different languages and technical terms of scientists and drilling engineers to minimise communication problems, problems which may lead to very cost-intensive bad decisions at the drillsite.

The training includes lessons about project management, drilling technique, borehole measurements and interpretation, data management, samples & sample handling and fundamentals of on-site geosciences. The lessons are taught by a team of instructors who are specialists in their fields and who have an extensive theoretical and practical experience. Specialists from the industry or scientific institutes will be engaged for special topics or individual courses if necessary.

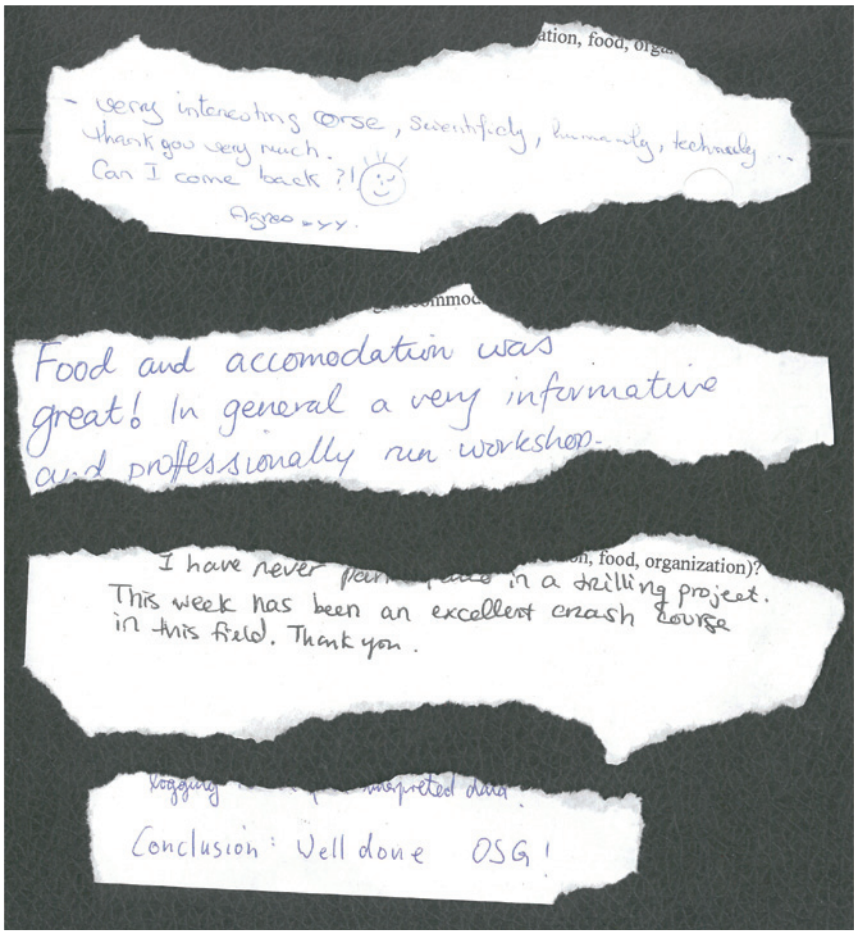


Figure 40. ICDP training course feedback

Since the founding of ICDP, 275 scientists, engineers and technicians from 37 countries, including all ICDP member countries, countries considering membership, and countries with ICDP drilling activities, have passed through ICDP training courses. ICDP is interested in integrating the training courses with active drilling projects and in holding the courses near a drillsite to bridge the gap between the classroom and practical application in the field. This will make the training as realistic as possible and maximise the training effect. The training courses last one week and are free of charge for the attendees.

in due time. A comment section will be provided where people can input as well as ask to become involved.

To the public

Target communities for public outreach measures include funding organisations and stakeholders, local communities, politicians and landowners, media, schools and universities and the interested public. Understanding cultural differences is a key element for the success of public outreach. Differences may include social customs, communication style and, last but not least, language. Therefore, public outreach activities including open days at drill sites, core repository visits, interviews, press releases and talks in schools and universities will be encouraged to get coordinated at a national level, ideally in cooperation between the project and the national ICDP office under consideration of national priorities. Material such as videos, brochures and flyers are available on the ICDP Website and will be developed further.

To develop a long-term outreach and education plan for ICDP, an ICDP outreach committee shall be launched including external experts for optimal output.

Figure 41. Young students with drill bit at the ICDP Snake River drill site, USA

EPILOGUE—ICDP IN ACTION

Figure 42. The Alpine Fault drill site, New Zealand

An external evaluation committee (2011) stated that ICDP is a leading global earth science infrastructure programme, enabling world-class science of global impact to be conducted with very modest investments.

The programme continues to be highly effective in community-building and is driving integration in modern earth system science:

- We focus our scientific effort on drilling sites of global significance (World Geological Sites).
- We stress affordability and cost-effectiveness through sharing—a boon for scientists and sponsors alike.
- Our projects are designed to attract high quality researchers to address topics of high national and international priority.
- There are clear intellectual benefits to all participants arising from international cooperation.
- We have our finger on the pulse of socio-economic needs linked to water quality, climate change, sustainable resource development and natural hazard vulnerability.

While the current 'lean and mean' management and financing system continues to work well, flexibility and growth are capped because of our membership funding structure and because subsidies from industry or other third-party sources are limited. It is ironic that ICDP, despite specialising in continentally based operations, and therefore ideally suited to encourage research projects with direct socioeconomic significance, attracts far less funding from national sponsors than does IODP. Attaining an overall higher visibility, as well as the streamlining of cross-organisational coordination, for example at a European level, is needed to generate increased funding from member countries. ICDP management and operational practices have been reviewed, and changes proposed to enable the programme to grow and flourish. The current model, with an honorary Executive Committee Chairman and a team of highly enthusiastic and supportive volunteers running the organisation, is not ideal. Full-time dedicated management ('professionalisation') is prerequisite, and two models are under consideration. Additionally, a key asset of ICDP, the Operational Support Group, already strongly subsidised by GFZ, needs more manpower and technical upgrading, and this will be implemented step-wise.

In closing, the future looks bright for ICDP. The Science Plan contained in this White Paper presents exciting cutting edge ideas on exploring the structure and workings of Earth's subsurface. Many of the drilling targets are confined to continental systems and therefore come under ICDP's auspices, but others transect the shoreline are therefore ideally suited for joint investigation alongside IODP. We seek to enhance throughput and diversity of projects while maintaining the highest level of science quality and providing added value for our sponsors. To make this happen, the management and operations business model has been revised, and we eagerly look forward to a new era in the illustrious history of ICDP.
Glück auf! *

*Glueck auf! is the German pitman's greeting

Figure Credits

Figure 1	p. 8	T. Wiersberg, ICDP, Germany
Figure 2	p. 9	J. Kück, ICDP, Germany
Figure 3	p. 10	ICDP, Germany
Figure 4	p. 11	K. Behrends, ICDP, Germany
Figure 5	p. 13	Y. Maystrenko, Geological Survey Norway and M. Scheck Wenderoth, GFZ, Germany
Figure 6	p. 14	O. Oncken and M. Motagh, GFZ, Germany
Figure 7	p. 15	T. Wiersberg, ICDP, Germany
Figure 8	p. 17	U. Harms, GFZ, Germany
Figure 9	p. 19	C. Knebel, ICDP, Germany
Figure 10	p. 20	M. de Wit, Nelson Mandela Metropolitan University, South Africa
Figure 11	p. 24	J. K. Nakata, U. S. Geological Survey, USA
Figure 12	p. 25	R. E. Wallace, U. S. Geological Survey, USA
Figure 13	p. 26	M. Bohnhoff, GFZ, Germany
Figure 14	p. 27	M. Bohnhoff, GFZ, Germany
Figure 15	p. 28	R. Conze, ICDP, Germany
Figure 16	p. 29	ICDP, Germany
Figure 17	p. 30	J. Mori, Kyoto University, Japan
Figure 18	p. 32	NASA, USA
Figure 19	p. 33	M. Schwab, GFZ, Germany
Figure 20	p. 34	A. Brauer, GFZ, Germany
Figure 21	p. 38	J. Schicks, GFZ, Germany
Figure 22	p. 42	T. Walter, GFZ, Germany
Figure 23	p. 43	T. Wiersberg, ICDP, Germany
Figure 24	p. 45	E. Huenges, GFZ / KIT (modified), Germany
Figure 25	p. 46	J. Salzer, GFZ, Germany
Figure 26	p. 49	T. Wiersberg, ICDP, Germany
Figure 27	p. 50	J. Matthey, Platinum Today image library
Figure 28	p. 51	L. Hecht, Museum für Naturkunde, Berlin
Figure 29	p. 52	ICDP, Germany
Figure 30	p. 56	S. Liebner, GFZ, Germany
Figure 31	p. 58	A. Gruner and R. Jarling, GFZ, Germany
Figure 32	p. 61	K. Pedersen, MICANS, Sweden
Figure 33	p. 66	NASA, USA
Figure 34	p. 69	ICDP, Germany
Figure 35	p. 75	Nice Martin Newspaper from, October 17, 1979
Figure 36	p. 75	A. Kopf, MARUM, Germany
Figure 37	p. 77	G. Mountain, Rutgers University, USA
Figure 38	p. 78	J. Adams, Wikimedia Commons
Figure 39	p. 81	T. Wiersberg, ICDP, Germany
Figure 40	p. 83	T. Wiersberg, ICDP, Germany
Figure 41	p. 84	ICDP, Germany
Figure 42	p. 86	J. Thompson, GNS Science, New Zealand

Imprint

Publisher: International Continental Scientific Drilling Program
GFZ—German Research Centre for Geosciences
Potsdam, Germany

Layout: TOMCOM (www.tomcom-design.de)

www.icdp-online.org