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A Decade of Progress, and Challenges for the Future

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With 94 Figures

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DR. ULRICH HARMS
GFZ Potsdam
Telegrafenberg
14473 Potsdam
Germany

Email: ulrich@gfz-potsdam.de

PROF. DR. CHRISTIAN KOEBERL
University of Vienna
Department of Geological Sciences
Althanstraße 14
1090 Vienna
Austria

Email: christian.koeberl@univie.ac.at

PROF. DR. MARK D. ZOBACK
Stanford University
Department of Geophysics
Stanford, CA 94305-2215
USA

Email: zoback@pangea.stanford.edu

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Foreword

Scientific drilling is an indispensable tool of modern Earth science research, as it provides the only means of obtaining direct information on processes operating at depth. Drilling allows for the determination of in-situ properties of solid materials and fluids and permits testing of hypotheses and models derived from surface observations. In addition, drill holes may be used as a natural laboratory for experiments and as observatories for long-term monitoring of on-going active processes. Earth drilling, therefore, plays a critical role in scientific research directed towards improved understanding of the workings of our planet and has a key role in solving urgent socio-economic problems.

As a rule, drilling projects are an integral component of major geoscientific research programs, comprising comprehensive pre-site investigations, accompanying laboratory studies, the drilling phase itself, and consecutive measurements and tests in the drill hole. Such drilling programs are costly and thus only realizable to a limited extent. International cost sharing, the optimal utilization of all available resources, the incorporation of international leading experts, and the application of the existing know-how, as well as the selection of an optimal drilling location ("World Geological Site"), are thus essential elements of an international scientific drilling program.

The International Continental Scientific Drilling Program, ICDP, founded in the year 1996, has amply demonstrated that these principal goals can be achieved. This volume summarizes the progress in scientific drilling on land during the past years and the plans of the science community to address challenging geoscientific problems by drilling in the forthcoming years.

More than 210 participants from 24 countries, representing a large variety of disciplines, attended the 2nd International Conference on Continental Drilling at the GeoForschungsZentrum Potsdam, Germany, under the title "Continental Scientific Drilling 2005 – A Decade of Progress and Challenges for the Future" from March 30 to April 1, 2005. The first day of the meeting served to provide an overview and review the past 10 years of research conducted within the framework of the ICDP. The second day of the meeting was used to develop visions for the future, to prioritize scientific questions and potential key locations. For this purpose, the conference split up into the eight breakout groups (Climate Change and Global Environment, Impact Structures, Geobiosphere and Early Life, Volcanic Systems and Thermal Regimes, Mantle Plumes and Rifting, Active Faulting, Collision Zones and Convergent Margins, Natural Resources). Results of the thematic working groups were presented during the third day in a plenary discussion aimed at defining the overarching goals and developing synergies.

The quintessence of the deliberations during the “Potsdam Conference” is presented in this book and will serve as a science plan for future internationally-coordinated and conducted scientific drilling projects on land.

Rolf Emmermann

Chairman, ICDP Executive Committee, GeoForschungsZentrum Potsdam, Telegrafenberg, 14473 Potsdam, Germany

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Author Index

Jan H. Behrmann
IFM-GEOMAR, Wischhofstr. 1-3, 24148 Kiel, Germany
e-mail: jbehrmann@ifm-geomar.de

Julie Brigham-Grette
Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA
e-mail: juliebg@geo.umass.edu

Scott R. Dallimore
Geological Survey of Canada, Sidney, British Columbia V8L 5S, Canada
e-mail: sdallimore@nrcan.gc.ca

Donald J. DePaolo
Department of Earth and Planetary Science, University of California, Berkeley, CA 94720-4767, USA
e-mail: depaolo@eps.berkeley.edu

John C. Eichelberger
Geophysical Institute, University of Alaska Fairbanks, AK 99775, USA.
e-mail: eich@gi.alaska.edu

Wilfred A. Elders
Department of Earth Sciences, University of California, Riverside, California 92521, USA
e-mail: wilfred.elders@ucr.edu

Gerald H. Haug
GeoForschungsZentrum Potsdam, Telegrafenberg, 14473 Potsdam, Germany
e-mail: haug@gfz-potsdam.de

Brian Horsfield
GeoForschungsZentrum Potsdam, Telegrafenberg, 14473 Potsdam, Germany
e-mail: horsf@gfz-potsdam.de

Hisao Ito
Center for Deep Earth Exploration, Japan Agency for Marine-Earth Science and Technology, Yokohama, Japan
e-mail: hisaoito@jamstec.go.jp

Thomas L. Kieft
New Mexico Institute of Mining and Technology, Socorro, NM 87801, USA
e-mail: tkieft@lanl.gov

Christian Koeberl
Department of Geological Sciences, University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria
e-mail: christian.koeberl@univie.ac.at

Bernd Milkereit
Department of Physics, University of Toronto, 60 St. George Street, Toronto, Ontario M5S 1A7, Canada
e-mail: bm@physics.utoronto.ca

Ze'ev Reches
School of Geology and Geophysics, University of Oklahoma, Norman, OK 73019, USA
e-mail: reches@ou.edu

Kozo Uto
National Institute of Advanced Industrial Science and Technology, 1-3-1 Kasumigaseki, Chiyoda-ku, Tokyo 100-8921, Japan
e-mail: k.uto@aist.go.jp

Dominique Weis
Department of Earth and Ocean Sciences, University of British Columbia, Vancouver, BC V6T 1Z4, Canada
e-mail: dweis@eos.ubc.ca

Jingsui Yang
Institute of Geology, Chinese Academy of Geological Sciences, 26 Baiwanzhuang Road, Beijing 100037, China
e-mail: yangjsui@ccsd.cn

History and Status of the International Continental Scientific Drilling Program

Ulrich Harms and Rolf Emmermann

GeoForschungsZentrum Potsdam, Telegrafenberg
14473 Potsdam, Germany
e-mail: ulrich.harms@gfz-potsdam.de (corresponding author)

Abstract

Multinational efforts in continental scientific drilling have been coordinated since 1996 within the International Continental Scientific Drilling Program (ICDP). The concept for this program was developed in response to an urgent requirement of the geoscience community for scientific drilling as a critical tool for a better understanding of fundamental Earth processes and structure. The program is based on commingled funding and international cost sharing, in addition to the joint international character of the science teams and sharing of technologies and know-how. It concentrates on topics of high international priority, and drilling projects are conducted at locations of global geological significance. The organization of the ICDP is simple and flexible comprising an independent review board, as well as an executive and an oversight committee. Administration assistance and a substantial operational support are provided voluntarily by the GFZ Potsdam in Germany. Funding is provided by a growing number of member countries, usually through national funding agencies.

ICDP fosters proposals through international workshops to assist in the development of a drilling proposal. In the first ten years of operations, 31 such workshops have been funded and have resulted in a total of 19 ICDP-supported and successfully executed drilling projects. Thematically the activities center around paleoclimate investigations, earthquake and volcanism research, impact events, geodynamics, and on unusual energy resources. A wealth of scientific results from these drilling and Earth observation projects has been published in scientific journals. Engineering, on-site science, and data management technologies developed within the past projects are another important component of ICDP. Based on an international conference in 2005, a refined science strategy for the future of program has been developed and is discussed in detail in the chapters that follow in this volume.

1 Development and Mission of the ICDP

1.1 Scientific Drilling

We live in a geologically complex world where Earth scientists are faced with tremendous challenges. Earth sciences must play a key role in satisfying society's ever-increasing dependence on natural resources, in meeting its needs to remediate existing environmental damage, in learning how to sustain human progress without causing further environmental degradation and in learning how to reduce our vulnerability to natural hazards.

A better understanding of the processes operating in the Earth's lithosphere and their interaction with the atmosphere, the hydrosphere and the biosphere is therefore essential for the wise management of the Earth's environment and resources. The geoscientific community has become increasingly aware of its responsibilities to provide decision-makers with this fundamental knowledge.

Great advances have been made in recent years in the conceptual understanding of the evolution of the Earth's continental crust; and modern techniques have also allowed great advances in geophysical and geological mapping of large areas. As a result it has become clear over the last decades that scientific drilling is a critical tool in our understanding of Earth processes and structure. Drilling can provide unique opportunities for the direct study of Earth processes and allows decisive testing of geological models developed on the basis of surface observations and remote sensing. Results obtained from drilling projects at critical sites can be applied to other areas worldwide. It is, therefore, believed that international co-operation in continental scientific drilling is an essential component for a responsible management strategy for the Earth's natural resources and environment.

1.2 Development of the ICDP

There has long been ad-hoc bilateral international co-operation in a number of scientific drilling projects. However, a multi-national continental drilling program, comparable to the very successful Ocean Drilling Program, was only established in the mid 1990s after a conference on the establishment of an International Continental Scientific Drilling Program and a number of successive meetings with representatives of funding organizations.

Because of the highly successful German Continental Deep Drilling Program KTB, Germany was asked to take a lead role and to organize an international meeting to examine the scientific justification and management needs for such a multilateral international program. This meeting was held from August 30 to September 1, 1993 in Potsdam, and was hosted by the then newly established GeoForschungsZentrum Potsdam (GFZ). The meeting was carried out under the auspices of the Coordinating Committee 4 “Continental Drilling” (CC-4) of the International Lithosphere Program (ILP) and strongly endorsed by the International Union of Geodesy and Geophysics (IUGG) and the International Union of Geological Sciences (IUGS). The scientific themes of the meeting were intended to be as comprehensive as possible, attempting to cover a broad spectrum of contemporary Earth sciences in order to discuss how scientific drilling could complement on-going geoscientific studies and make it possible to address fundamental, unresolved questions critically relevant to both societal needs and an improved understanding of the Earth and its lithosphere.

These questions were discussed in detail by the 250 experts from 28 countries present at the meeting. The results of this first “Potsdam Conference on Continental Scientific Drilling” are reported in a voluminous brochure “Scientific Rationale for Establishment of an International Program of Continental Scientific Drilling” edited by M. Zoback and R. Emmermann, and published in 1994.

Following the Potsdam Conference, science managers from 15 participating countries met at Windischeschenbach, the site of the German Continental Deep Drilling Program, to consider formally the establishment of an ICDP.

The science managers nominated a preparatory group who got the mandate to draft a concept for the structure, operation and funding of an International Continental Scientific Drilling Program (ICDP) by addressing issues such as:

- An overall structure for management of the program,
- The sponsorship of the program,
- Mechanisms for the management of projects of various dimensions,
- Design of program structure,
- Criteria for selection of projects,
- Mechanisms for promoting international participation.

In March 1994 an agreement under the umbrella “Cooperation in Research in Geosciences” between the US National Science Foundation (NSF) and the German Federal Ministry for Education, Science, Research and Technology (BMBF) was signed. The ICDP started officially on February 26, 1996 when the MOU was ratified by representatives of the US National Science Foundation, the Chinese Ministry of Geology and Mineral Resources and the German Federal Ministry for Education, Science, Research and Technology /GeoForschungsZentrum Potsdam (GFZ) at the German Embassy in Tokyo. Parallel to the formal signature, the three main panels in the organizational structure of the ICDP were formed: the Assembly of Governors (AOG), the Executive Committee (EC) and the Science Advisory Group (SAG) and a first call for proposals was issued in EOS and other international journals. The first proposals were reviewed by the SAG and decided on by the EC and the AOG at the end of 1996.

1.3 Mission of the ICDP

The general requirements for an International Continental Scientific Drilling Program as agreed upon at the Potsdam Conference are that:

- It addresses fundamental scientific problems of global importance as an element of geological and geophysical research programs.
- It seeks geological sites from around the world and involves the international community of scientists to optimize the results from drilling.
- It involves both shallow and deep drilling to address specific questions.
- It is proposal-driven, peer reviewed and operated on the basis that the scientific findings of the program should have broad impact on ongoing research throughout the world.
- It is organized in such a way that it will be possible from both a managerial and technical perspective to meet the varied needs of the Earth science community.
- It is a continuing program with an operational framework which fosters international collaboration and evolving technical capability.

The principal advantages of such an international program of appropriate scale and viability are:

- Focusing of scientific effort on drilling sites of global significance (World Geological Sites).
- Affordability and cost-effectiveness through sharing.
- Attraction of high quality researchers to topics of high national and international priority.
- Intellectual benefits to all participants arising from international cooperation.

These general considerations led to the following mission of the ICDP:

> “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”

with particular focus on research themes such as:

- The physical and chemical processes responsible for earthquakes and volcanic eruptions, and optimal methods for mitigating their effects.
- The manner in which Earth's climate has changed in the recent past and the reasons for such changes.
- The effects of major impacts on climate and mass extinctions.
- The nature of the deep biosphere and its relation to geologic processes such as hydrocarbon maturation, ore deposition and evolution of life on Earth.
- How to safely dispose radioactive and other toxic waste materials.
- How sedimentary basins and hydrocarbon resources originate and evolve.
- How ore deposits are formed in diverse geologic settings.
- The fundamental physics of plate tectonics and heat, mass and fluid transfer through Earth's crust.
- How to better interpret geophysical data used to determine the structure and properties of Earth's crust.

2 Structure and Management of the ICDP

2.1 Organizational Structure of the ICDP

The overall objective of the program structure is to maintain autonomous drilling projects of any type, independently organized and managed in the form of a **Joint Research Venture** with national, bi-national, or multinational partners, connected through an ICDP funding contribution and committed to certain principles in scientific cooperation and exchange.

The structure, which is shown in Fig. 1, is designed to facilitate the following main functions:

1. Oversight and determination of policy - by the **Assembly of Governors (AOG)**.
2. Program management and operation, including project prioritization and budget allocation - by the **Executive Committee (EC)** with its legal non-profit entity, the so-called **Operational Support Group (OSG).**

3. Scientific assessment of project proposals submitted for ICDP participation- by the **Science Advisory Group (SAG)**.
4. Project management - by teams in host countries under the leadership of Principal Investigators (PIs).
5. Project monitoring - by the Executive Committee, for reporting to the Assembly of Governors.

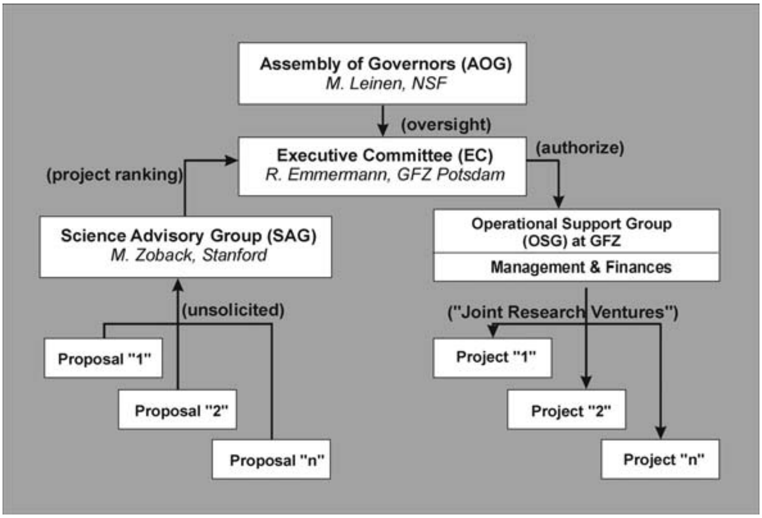

Fig. 1. Organizational structure of the International Continental Scientific Drilling Program, ICDP.

2.2 ICDP Boards

2.2.1 The Assembly of Governors (AOG)

The AOG provides financial and scientific oversight, makes major policy decisions and reviews the acceptance of members. It is composed of one representative from each member country. Decisions of the AOG are made through a consensus process guided by the chair. The AOG holds annual meetings convened by the chair, who has the authority to call special meetings should the need arise.

2.2.2 The Executive Committee (EC)

The AOG authorizes the EC to manage the ICDP. The EC is made up of one appointee from each ICDP member. It has the responsibility to assemble the scientifically prioritized projects of the Science Advisory Group into an annual program plan with an associated annual budget that constitutes the ICDP Program.

The EC reports annually to the AOG on the past year's operational activities, ICDP budget, and scientific accomplishments.

2.2.3 The Science Advisory Group (SAG)

The SAG is an independent body of internationally renowned experts in the research fields covered by ICDP projects. It has the task of carrying out a thorough scientific evaluation of the individual competing proposals submitted to ICDP and to compile a priority list based on expected scientific merits. The recommendations of the SAG are the primary input to the EC as it develops projects for both annual and long-range programs.

Members of the SAG are nominated by the respective member organizations of the ICDP or selected by the EC in consultation with international organizations such as the International Lithosphere Program.

2.3 The Operational Support Group (OSG)

The EC is served by the so-called Operational Support Group, which provides the EC with the operational capabilities to manage the program and to support individual ICDP projects as determined by the terms of the Joint Research Ventures. The OSG is a not-for-profit entity under German Law at, and separately financed by, the GeoForschungsZentrum Potsdam. It has the following support functions:

- Provide technical and scientific liaison to SAG and EC.
- Develop Joint Research Ventures for each project authorized by EC.
- Management and support of secretariats for AOG and EC.
- Assistance in contracting and permitting.
- Support for scientific and engineering drill-site operations.
- Support for field facility for core and sample description and management.
- Provide all data collected during each project through a readily accessible data management system for ICDP projects, the “Drilling Information System” (DIS).
- Prepare - through this DIS - initial reports that describe drilling, engineering and sample and core description and procedures for each project.
- Provide training courses in scientific drilling as “training on the job” or in preparation of other future drilling projects.

- Develop, purchase, and maintain an ICDP equipment pool comprising scientific-technical instruments and tools for on-site use in ICDP projects.
- Provide management support for individual ICDP projects.
- Provide and operate ICDP equipment.

The GFZ Potsdam currently finances - from its own budget - a group of six scientists, engineers, and technicians, who compose the core of the ICDP Operational Support Group. This group is a separate organizational unit at the GFZ. The OSG comprises the following expertise and respective duties:

- Drilling engineering.
- Support for drilling contracting, technical design of drilling projects and drill-site operations, drilling engineering developments, on-site drilling and financial supervision of individual projects, drilling tool supervision of ICDP equipment pool etc.
- Instruments and training.
- Organization of on-site technical and scientific instruments of the ICDP equipment pool, organization and execution of training courses.
- Advice, organization and execution of downhole-logging campaigns, logging data control, development, purchase and maintenance of logging tools, organization of “downhole” equipment pool of ICDP.
- Downhole logging.
- Maintenance and repairs of downhole instruments, winches, and related tools, logging data acquisition and storage.
- Data management.
- Set-up and operations support of the DIS and data management for ICDP, website organization and update.
- Support in ICDP program management and liaison with the Integrated Ocean Drilling Program (IODP).
- Secretariat for the EC and AOG, proposal handling, JRV negotiations and other contractual issues, financial project management and budgeting, GFZ in-house liaison to administration.

On an “as-needed basis” other scientists and technicians of the GFZ Potsdam provide additional support for the ICDP for a limited time period, e.g. during downhole-logging campaigns, on-site repair of tools or to support the ICDP data management. Should additional technical or scientific expertise be needed, the OSG can, upon approval of the EC, employ further staff who is financed from ICDP funds for limited time periods.

2.4 The GeoForschungsZentrum Potsdam as Executive Agency

The GFZ Potsdam is the Executive Agency of the ICDP and acts on behalf of the ICDP members. The GFZ was founded in 1992 as one of three new "Big Research Centres" in East Germany. It is a Foundation of Public Law, belongs to the Helmholtz Association of Germany Research Centres and represents the German National Research Centre for Earth Sciences. It currently has about 650 employees (including about 330 scientists).

The ICDP Operational Support Group (OSG) is a separate unit within this structure and directly assigned to the Scientific Executive Director. The scientific executive director is currently chairman of the EC of the ICDP. Together with the OGS and members of the staff of the Scientific Executive Board he is responsible for the overall management of the ICDP. The administrative executive director is responsible for the administration of the ICDP money, the control of the expenditures and all judicial business related to the formulation and negotiation of contracts such as the memoranda of understanding, joint research ventures and other national or international agreements. He is assisted by the staff of the administrative executive board and the department "Budget and Finances" within the Administration of the GFZ. Proper expenditure of ICDP money is controlled annually by an external auditing company.

2.5 ICDP Membership

ICDP was officially founded in February 1996 at a meeting at the German Embassy in Tokyo. The founding members were the United States (represented by the US National Science Foundation), China (represented by the Chinese Ministry for Land and Resources), and Germany (represented by the Federal Ministry for Research and Technology and by the Deutsche Forschungsgemeinschaft). The number of members has continually increased during the past years.

ICDP currently has 15 members. These include 13 countries (Germany, USA, Japan, China, Canada, Austria, Mexico, Norway, Poland, Czech Republic, Iceland, Finland, and South Africa), the UNESCO and Schlumberger Services Inc. as a corporate affiliate. Negotiations on membership are currently underway with several European countries.

2.6 ICDP Finances

ICDP is financed through the annual contributions of its members. The membership fees vary and are based on a number of criteria that include economic factors, the scientific manpower and size of the respective country, and the comparability to ICSU membership fees. Corporate affiliates are reserved for industrial partners or for private research groups that wish to participate in the ICDP. They have access to the scientific projects of the ICDP and are invited to participate in the planning process.

2.6.1 ICDP Expenditures

The ICDP funds are used, for the most part, for co-funding of the approved ICDP projects and for the execution of ICDP workshops and training courses. In addition, funds cover expenditures for the maintenance of the ICDP equipment pool and the ICDP DIS.

Costs for the ICDP board meeting are very low and amount to a maximum of 3% of the annual overall expenditure. No costs occur for the administration of ICDP money through the GFZ Potsdam. The ICDP funds and expenditures are managed by the finance department of the GFZ.

2.6.2 Funding of ICDP Projects

The philosophy of ICDP is based on the “commingled funding” principle. This means that the ICDP is usually one of several funding partners in a joint drilling project. The financial contribution of the ICDP to an ICDP-supported drilling project varies between about 5% to about 70% (in rare cases) of the total operational costs. The mean value over the past 10 years has been 18%.

The ICDP contribution to a scientific drilling project reviewed by the SAG, recommended by the EC and approved by the AOG is negotiated for each project between the GFZ Potsdam and the respective principal investigators and laid down in the joint research venture.

2.7 Proposal Submission, Review and Project Development

2.7.1 Proposal Submission

Scientists from member countries or countries considering membership have the right to submit unsolicited proposals to the ICDP. Proposals may be assembled by individuals or groups of scientists from single or groups of countries. Proposals to the ICDP are each year requested through a Call for Proposal published in two or three advertisements from October to December in EOS (the Transactions of the American Geophysical Union) and on ICDP’s webpage. The deadline for proposal submission is always January 15 each year. For details on how to submit a proposal, including detailed guidelines, see: http://www.icdp-online.org.

2.7.2 From Proposal to Project

The development of a proposal submitted to ICDP into an ICDP co-financed scientific drilling project normally follows a procedure that is graphically represented in Fig. 2.

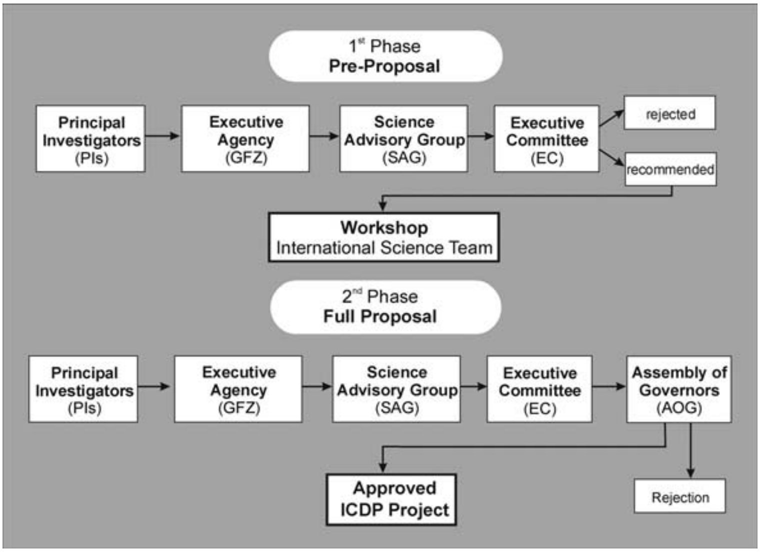

Fig. 2. ICDP Project development scheme.

The individual steps are:

1. Submission of a pre-proposal (letter proposal) by the principal investigators (PI) to the GeoForschungsZentrum Potsdam (OSG)
2. Review and ranking of the letter proposals by the SAG
3. Discussion and assessment of the evaluation by the EC, which either leads to a rejection or a recommendation to go ahead with the development of a full proposal
4. If a pre-proposal is encouraged, the PIs may request funds from ICDP for an international workshop to develop a sound full proposal
5. Following a successful workshop a full proposal can be submitted to ICDP for a detailed review by the SAG and a final recommendation by the EC.

At this stage of project development the PIs can request advice and support in all matters related to the scientific and technical realization of the planned project from the OSG.

Full proposals must include detailed information on the scientific goals of the project, the expertise of the PIs, the status of commingled funding, design and management of the project, long-term curation etc. The final decision on an ICDP co-funding is made by the AOG based on recommendation of the EC.

Once a full proposal is approved, the EC gives authority to the OSG to support the PIs in all matters related to the final planning and conduction of the drilling project and to negotiate a Joint Research Venture. Each project is organized in the form of a national, bi-national or multi-national JRV between the ICDP and the PIs and other interested parties such as government agencies, funding organizations or companies. The JRV specifies the scientific goals and the respective funding responsibilities, operational procedures and conditions of technical cooperation and exchange for all partners in a specific project. In addition, it defines the financial contribution of the ICDP and other partners/organizations that contribute to the "commingled funds".

2.7.3 Main Criteria for Selecting ICDP Projects

Selection of project proposals for ICDP co-funding is based primarily on scientific merits and the expected impacts on the Earth sciences but also includes secondary considerations such as permitting, environmental concerns, technical difficulties, safety issues, etc. Successful project proposals have to meet the following five main criteria:

- **International Criterion -** ICDP projects should be international in scope in order to choose the very best targets, to optimise scientific yields, and to pool technological and financial resources.
- **Global Criterion** - The ICDP should select drilling targets, which are ”world class” and represent problems of global significance, rather than just local problems.
- **Need-for-Drilling Criterion -** The ICDP should only choose drilling projects where it can clearly be shown that the necessary information is not otherwise obtainable than by drilling, or which exploit the unique environment of the borehole.
- **Societal-Needs Criterion -** The ICDP projects, where appropriate, should strive to collaborate with industry, and not only be concerned with purely academic issues. Where possible it should give preference

to projects that have some relevance to societal needs, such as energy and mineral resources and geological hazards, etc.

- **Depth-and-Cost Criterion -** The ICDP projects should try to be cost effective by minimizing the depth, difficulty, and hence cost, of the drilling targets selected, by judicious choice of the best possible locations worldwide for the classes of phenomena being investigated.
- **Active-Processes Criterion -** The ICDP should put special emphasis on the study of active rather than ancient systems. Drilling projects should focus on projects where drilling provides crucial information, not otherwise obtainable, including rock and fluid composition, temperature, pore fluid chemistry, state of stress, etc.

2.7.4 Proposals Submitted to ICDP

From 1996 to 2005 the ICDP has received a total of 144 proposals. These include letter and full proposals, workshop proposals and proposals related to the development of tools and instruments for the ICDP equipment pool. A total of 121 proposals referred to drilling projects.

3 ICDP Co-financed Activities

3.1 ICDP Workshops

ICDP funded or co-funded international workshops constitute an essential component in the preparation of a competitive full proposal for an ICDP drilling project. These workshops allow the PIs to invite the experts in the respective research field from all over the world, to broaden their scientific program, to establish an international science team and to prepare a detailed science, operations, and budget plan.

Until summer 2006 31 ICDP-funded workshops have been carried out and several more are already in the planning stage (see Table 1). ICDP workshops are announced in EOS and offer scientists from all over the world to apply for participation. The announcement is prepared in close cooperation between the PIs of the respective projects and the OSG. Most workshops were held at locations close to the planned drill site to allow for a one day scientific field excursions and local facility inspection. The meetings are usually attended by 30 to 50 participants.

Table 1. Themes of past ICDP-funded workshops

Theme	Venue and Date	Participation
Understanding Lacustrine Environmental History through Continental Drilling	New York, USA, December 1996	40 participants from 4 countries
Unzen International Workshop: Decade Volcano and Scientific Drilling	Shimabara, Japan, May 1997	75 participants from 7 countries
Pre-site Selection of Scientific Drilling in the Dabie-Sulu UHPM Region	Qingdao, China, August 1997	60 participants from 5 countries
Large Lake Drilling Technique	Miami, USA, October 1997	20 participants from 2 countries
Development of a multi-borehole Observatory at the Gulf of Corinth	Athens, Greece, October 1997	52 participants from 7 countries
Drilling Lake Titicaca	Huatajata, Bolivia, May 1998.	32 participants from 5 countries
Tectonic evolution and mechanics in the extending forearc of the retreating Hellenic subduction zone	Chania, Greece, October 1998.	35 participants from 9 countries
Drilling into the Chicxulub Impact Structure, Mexico	Merida, Mexico, March 1999	35 participants from 6 countries
International Workshop for a Climatic, Biotic, and Tectonic, Coring Transect of Triassic-Jurassic Pangea	Wolfville, Canada, June 1999	56 participants from 13 countries
Scientific Drilling on Lakes Malawi and Tanganyika	Malawi, October, 1999	57 participants from 9 countries
The Unzen Scientific International Drilling Workshop	Shimabara, Japan, October 2000	35 participants from 5 countries
Bosumtwi Crater Drilling Workshop	Potsdam, Germany, September 2001	30 participants from 10 countries
Chelungpu Fault Drilling Workshop (Part 1)	Taipeh, Taiwan, September 2001	60 participants from 5 countries
El´gygytgyn Crater Lake PreDrilling Workshop	Amherst, USA, November 2001	26 scientists from 4 countries
Chelungpu Fault Drilling Workshop (Part 2)	Stanford, USA, December 2001	30 participants from 3 countries
Dead Sea Drilling Workshop	Luckenwalde, Germany, January 2002	30 participants from 7 countries
Iceland Deep Drilling Workshop 1	Nesjavellir, Iceland, March, 2002	49 participants from 7 countries
Drilling Active Faults in South African Mines	Parys, South Africa, Sep 2002	70 participants from 6 countries

Table 1. continued

Theme	Venue and Date	Participation
Iceland Deep Drilling Project Workshop II	Nesjavellir, Iceland, Oct 2002	73 participants from 8 countries
Japanese Ultradeep Drilling and Experiments, JUDGE	Chiba, Japan Nov, 2002	100 participants from 6 countries
Lake Biwa and Lake Suigetsu Project Workshop	Kyoto, Japan, Nov 2002	57 participants from 6 countries
ICDP Workshop on Scientific Drilling in Lake Peten Itza	Flores, Guatemala, Aug 2003	35 participants from 9 countries
Exploring the African-European suture at depth: Orava Deep Drilling Project (ODDP)	Zakopane, Poland, Aug/Sep 2003	66 participants from 13 countries
Anatomy of an Impact Basin: Scientific Drilling of the Sudbury Structure	Sudbury, Canada, Sep 2003	78 participants from 8 countries
Deep Drilling in the Central Crater of the Chesapeake Bay Impact Structure, Virginia, USA	Reston, VA, USA, Sep 2003.	60 participants from 10 countries
Scientific Drilling at Qinghai Lake on the northeastern Tibetan Plateau: High resolution paleoenvironmental records of eastern Asia	Xining, China, Oct 2003.	57 participants from 8 countries
Drilling the Eger Rift Workshop	Bykov, Czech Rep., Oct 2004	45 participants from 8 countries
International Planning Workshop for Scientific Drilling - Archaean-Palaeoproterozoic Transition: Emerging Modern Earth System	Trondheim, Norway, Sep 2005	28 participants from 9 countries
Potrok Aike Lake Sediment Archive Drilling Project, southernmost Argentina (PASADO)	Rio Gallego, Argentina, Mar 2006.	52 participants from 11 countries
Intermediate Depth Drilling of the Snake River Plain: Tracking the Yellowstone Hotspot through Space and Time	Twin Falls, Idaho, USA, May 2006.	60 participants from 6 countries
ICDP-IODP Workshop on Fault Zone Drilling: Developing the Global Perspective	Miyazaki, Japan, May 2006.	83 participants from 9 countries
Lake Van Drilling Project– PaleoVan	Van, Turkey, Jun 2006.	40 participants 11 countries

3.2 ICDP Co-Financed Drilling Projects

Since the first ICDP co-financed drilling campaign on the Lake Baikal in 1998, a total of 19 international drilling projects (Fig. 3) have been carried out world-wide, and several others are about to start or are in the preparatory phase. The drilling projects deliver a significant contribution to ten major themes of Continental Scientific Drilling as identified in the “Scientific Rational for Establishment of an International Program of Continental Scientific Drilling” in the year 1993, see listing below.

- Impact Structures and Mass Extinctions.
- Earth History and Climate.
- Evolution and Physical Processes of Sedimentary Basins.
- Lithospheric Dynamics and Deformation.
- Volcanic Systems and Thermal Regimes.
- Convergent Plate Boundaries and Collision Zones.
- Fluids in the Crust.
- Geophysics of the Crust.
- The Deep Biosphere.
- Natural Resources and Origin of Mineral Deposits.

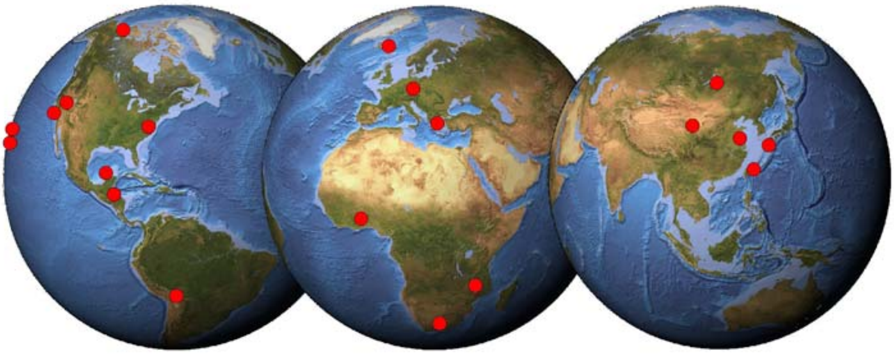

Fig. 3. World map with locations of ICDP drilling projects as of 2006 (figure-background: NASA/JPL/NIMA).

A brief description of the projects supported by and conducted under ICDP auspices is given in the appendix of this chapter. The ICDP website provides further details including DIS data, sample photos, as well as all science team members (www.icdp-online.org).

3.3 ICDP Training Courses

Scientific drilling is developing more and more into a powerful and indispensable tool in Earth sciences. Unfortunately, however, drilling is not taught in Earth science at universities world-wide. Therefore, an important component of the ICDP is the capability to train Earth scientists, engineers, and technicians in drilling-related technologies. This includes courses relating to project management, drilling techniques, borehole measurements and interpretation, data management, sample handling and fundamentals of on-site geosciences. The current basis of ICDP training is a set of ten courses covering the following topics:

- Planning and managing of a scientific drilling project.
- On-site geology.
- Petrophysical investigation of cores and cuttings.
- Fundamentals of drilling technology.
- The principles of drilling fluid technology.
- Borehole stability.
- Hydraulic testing/fluid sampling.
- Basic borehole logging and interpretation.
- Log interpretation in the non-hydrocarbon environment.
- Information and data management.

The training program is arranged either at the GFZ Potsdam or as a project-related course directly at the location an ongoing drilling project. The OSG is interested in integrating a running drilling project in the program and to hold the courses near a drillsite in close cooperation with the particular principal investigators, responsible scientists, and engineers. This approach is intended to bridge the gap between the classroom and practical application in the field and to make the training as realistic as possible for maximization of the training effect. The twelve courses taught from 1997 to 2004 have been conducted in China, Germany, Japan, USA, Mexico, and Ghana and have been attended by altogether 104 participants from up to 7 countries.

3.4 ICDP Operational Support

Financial support for drilling operations of ICDP co-funded projects are complemented by logistic, engineering, and scientific-technical support through the OSG. In addition, ICDP funds have also been used to acquire instruments and tools necessary on-site for scientific-technical purposes.

The tools purchased or developed for an individual project are after a first use integrated in the ICDP equipment pool for following projects.

3.4.1. Drilling Engineering Support

A majority of scientific drilling projects require "near-continuous coring" which is usually realized through "wireline coring". For deep drilling, a specially designed drill string with inner core barrel allowing for core recovery through the string has to be used. Therefor, an oilfield-type drill rig has to be equipped with a top-drive system. ICDP used the DOSECC Hybrid Coring System which has been developed for the Hawaii Drilling Project. This coring system can be accommodated by a large variety of host rotary rigs. During coring operations, standard wireline coring rods are used with thin-kerfed diamond bits drilling a 100 mm hole and cores of 63 mm diameter. For drilling projects requiring a larger drilling and core diameter the OSG developed a special drill string that drills a 152 mm holes with a core diameter of 94 mm. To rotate this drill string a top-drive system was purchased by ICDP.

Several project proposals clearly demonstrated a necessity to collect long, continuous cores from lakes for paleoclimate, environmental, and impact research. Therefore, a drilling system called Global Lake Drilling Facility with 800 m depth capacity (GLAD800) was developed and is operated in a joint venture between DOSECC and ICDP. GLAD800 is a modified conventional small drilling rig, transported in a set of containers that are deployed as a barge for drilling. This system is able to collect 62 mm cores from up to depths of 800 m (water + sediments).

Because scientific drilling projects do not end with drill operations but require especially in tectonically active regions long-term monitoring at depth to allow for acquisition of unique in situ data. An extended monitoring phase in usually hostile pressure and temperature conditions needs new well completion techniques for the application of long-lasting, drift-free instrumentation. New high-precision permanent monitoring arrays and sensors are currently being developed to observe stress and strain, fluid composition and activity, temperature, and seismic unrest.

In the following paragraphs a few examples demonstrate the engineering support provided so far by the OSG for various projects.

Dabie-Sulu (China). The objective of the Chinese Continental Scientific Drilling Project (CCSD) was to drill and to investigate a 5000 m deep hole in ultra-high pressure metamorphic rocks. From the technical point of view the project is very similar to the KTB. Therefore, the experiences gained in the German project were applied for the development of the drilling strategy, the technical concept and the scientific on-site program. This was realized through several meetings and special training programs for Chinese engineers and scientists. The technical support by the OSG included also the purchase and production supervision of a hydraulic top-drive system and a special wireline coring string of 5.5 km length. Within the CCSDP, a combination of the conventional rotary drilling technique with a new coring technique, developed in China, namely coring with downhole motor and hydraulic hammer was applied.

Chicxulub (Mexico). The first deep drilling and coring project into one of the largest well-preserved impact structures on Earth was executed in winter 2001/2002 in the 65 Ma old Chicxulub crater in Mexico using integrated coring sampling and in situ measurements. The OSG was responsible for the technical project management of the Chicxulub Scientific Drilling Project (CSDP). This included development of a drilling strategy and the borehole design, negotiations and contracting with drilling companies, supervision of all drilling activities and controlling of budget and safety.

San Andreas Fault Zone Observatory at Depth (USA). The SAFOD project is part of the EarthScope program of the National Science Foundation being carried out in conjunction with the U.S. Geological Survey. The OSG has been contributing to the technical realization of the project by development of the drilling strategy and borehole design, supervision of the drilling activities, budget and safety controlling, as well as the design and implementation of a long-term in situ monitoring string.

3.4.2 Geophysical Downhole Logging

Many ICDP projects do not have a budget for a comprehensive or an oilfield-type geophysical downhole measurement program. The OSG has, therefore, purchased a variety of geophysical logging tools (Fig. 4) and established a logging sub-group that provides assistance in preparation, management and performance of logging programs in ICDP co-funded projects. The possibility to acquire a basic set of geophysical and structural in situ information even under tight budget constraints is a main benefit of the OSG logging capabilities. Since 1999, the OSG performed a total of 16 downhole logging campaigns at nine ICDP projects. The permanent two-man OSG logging crew is routinely enforced during field operations by personnel from other GFZ departments. The petrophysical and structural parameters that can be acquired with the ICDP slimholes holes comprise:

- electrical resistivity

- natural gamma spectrum
- sonic
- magnetic susceptibility
- magnetic field
- structures

The borehole diameter must be at least 55 mm, the maximum borehole temperature temperature 150°C and a pressure limitation of 80 MPa exists. The tools are fully digital with oilfield standard resolution. As the OSG identified a growing demand for a winch system covering the depth range from 0 – 2000 m in particular for lake drilling projects a small and light-weight, electrically driven winch system able to handle 2000 m of a four–conductor logging cable was purchased with ICDP money. The system was first used successfully in the Lake Bosumtwi project in August 2004.

Fig. 4. Photo of slimhole geophysical logging sondes comprising electrical resistivity, natural gamma spectrum, sonic, magnetic susceptibility, magnetic field, as well as structural ultrasonic image tool.

3.4.3 ICDP Data and Information Management

Data and information management is one of the basic value-added scientific services for ICDP projects. It is based on two legs:

1. The DIS is designed to acquire and manage the scientific drilling data,

2. The ICDP webhouse is set up as a long-term archive and data warehouse to retrieve and disseminate the data through a common web interface. Both “legs” were developed by the OSG in co-operation with the Data Centre of the GeoForschungsZentrum Potsdam. They are meanwhile available in a version suitable, tested, and modified for on-shore and off-shore drilling projects.

As ICDP projects cover a wide range of geological settings and scientific targets an all-in-one solution for data management considering all possible aspects of scientific drilling is not possible. Consequentially, the concept for the ICDP data and information management is open and project-oriented, in such a way that each drilling project determines the milestones of the software development and data model design.

ICDP Information Network. The main objective of the ICDP information network is to provide comprehensive data and information management for all ICDP projects. The information network encompasses services supporting:

- The capturing of scientific drilling data using the special on-site DIS,
- a virtual global field laboratory based on the e**X**tended DIS,
- the dissemination of project information via a common ICDP web site (Fig. 5),
- the integrated evaluation and analysis of data supported by the ICDP webhouse.

With the idea to set up a comprehensive, top-down, all-inclusive information system, the OSG concentrates preferentially on the operational and scientific phases of drilling projects until the main publications have been finalized. Nowadays, the long-term archiving and publication of data as well as catalogue services are provided by higher authorities, such as World Data Centers and electronic libraries.

DIS Training. As soon as a proposal for a drilling operation has been approved, the PIs are contacted to specify their needs and to designate one or two data curators. These persons are usually sent for a specific two weeks DIS training to Potsdam. During this course the expected on-site situation, the logistics, the infrastructure, staffing, and the scientific data types are analyzed in detail. Accordingly, a first project-specific DIS is designed and set up on a preliminary DIS server, usually a laptop provided by the project.

On-site Data Management. The on-site data management usually starts a week before the drilling operations begin. The OSG assists the data curators in setting up the local network, in preparing the DIS-server and DISclient machines, in testing and adjusting the DIS according to necessary requirements.

Fig. 5. ICDP home page *(www.icdp-online.org)* with locations of drilling projects.

Core Imaging. The digital core scanning facilities are an integral part of the DIS systems, which are used for the documentation of the fresh cores. According to the rock types (soft or hard rock cores), and the scientific requirements it is possible to scan the 360° unrolled core and/or the split core face. The digital images can later be used as documents of the initial lithological description and for distinct image analyses. ICDP has purchased and used four color scanning tools (company DMT) at meanwhile 10 different projects; meanwhile a fifth instrument has been used a lightweight core image system developed (company *smartcube*), see Fig. 7.

Remote Administration. After the on-site support, the data curators can request for remote assistance or even remote administration in the remaining time of the project. In most cases, email communications and ftp-transfer are sufficient to solve smaller questions or updates. In more severe cases a terminal service to the DIS-server is used to maintain the database system directly. Usually, the OSG controls the progress and quality of the data acquisition through the DIS-FTP tool and XDIS Web interface without any direct interaction with the on-site system.

Project Web Site. Each ICDP project has its own project Web site with the ICDP Information Network. This platform is used to provide general information about the objectives, the location, the participating scientists and their proposals, the publications, and current news from the drill site or the laboratories. Most of these contents are provided by the project PIs and other science team members. Data from the drilling operation, the core or cutting recovery, initial lithological descriptions and other petrophysical or geochemical measurements are added as soon as available. The PIs decide which data and information can be public, and which should be restricted for the defined period of confidentiality.

ICDP Data Marts. For each ICDP project, the recorded primary data and additional analytical data are automatically propagated from the field labs to the internal network at GFZ, and stored in so-called data marts of the ICDP data warehouse. During that transfer, incoming data are quality-assured, suitable metadata are assigned, data completeness and naming conventions are checked. As soon as the data sets are consolidated, the contents of the data marts are transferred into a reliable data archive which is the prerequisite for putting it online. Finally, digital identifiers are applied to the selected data sets for being published through common World Data Centers.

Core Handling and Sampling. The GFZ Potsdam agreed to provide all facilities and equipment for a basic analysis and the storage of the impact cores of the Bosumtwi Crater Drilling Project including managing a sampling party and sample deliverance to all involved scientists. The OSG installed a core lab with core logging and scanning equipment and a binocular for a basic description and interpretation of the cores. About twenty scientists participated in the sampling party conducted by the OSG in January 2005. The cores are now stored at the GFZ and are accessible for further studies.

4 Impact of the ICDP

4.1 Technological Innovations

The scientific challenges addressed by ICDP projects evoked several technological developments and new tools. Novel techniques for onsite facilities were often needed in ICDP projects, but were not available from the hydrocarbon-oriented service companies. High-tech equipments and facilities, such as hard-rock or unconsolidated lake-bed coring tools are not needed in oilfield drilling, and stress and strain monitoring in fault zones are no targets for gas extraction processes. Therefore, the ICDP, either through the project teams or the OSG, has developed concepts and tools which are purpose-fit to scientific drilling, and which have become part of the ICDP equipment pool for further use and improvement. Some of the most important examples of technological innovations inspired by and driven through the ICDP are listed below.

Lake Sediment Coring Systems. The Lake Baikal Drilling Project experienced low core recovery in the first expeditions due to a lack of appropriate coring tools. Supported by ODP-based experience, new integrated exchangeable coring tools comprising a “Rapid Piston Sampler”, a “Hydraulic Percussion Sampler”, and a “Rotary-Percussion Corer”, were developed by the Russian drilling companies NEDRA and Aquatic for the Baikal Drilling Project.

Hybrid Coring System. Wireline coring systems integrated in rotary drill rigs are an adequate facility combination to achieve continuous high-quality coring in deep crystalline drilling. The ICDP-funded projects Long Valley and Hawaii planned to apply such systems through service industry contracts. Because a suitable system was commercially not available, the U.S. National Science Foundation financed the development of a special Hybrid Coring System, which was also used for the Chicxulub drilling.

GLAD 800 and Dynamic Positioning System. The Global Lake Drilling Facility GLAD800 was developed and funded by ICDP in cooperation with the U.S. scientific drilling organisation DOSECC to provide a novel, compact, cost-effective, powerful, mobile, wireline-coring rig with special coring tools and a platform strategy (Fig. 6). Lacustrine sediment cores in most of the world's lakes can be retrieved with this facility from up to 800 m depth. The initiative was driven by a need to obtain continuous sediment cores providing long-records in order to understand millennial and glacial/interglacial-scale paleoclimate patterns, abrupt event synchroneity, and natural variability. The GLAD800 has so far been used for the ICDP projects Titicaca, Bosumtwi, partly in Malawi, Qinghai, and Peten Itza. A Dynamic Positioning System was added in order to allow for station keeping in deep lakes such as in the Lake Malawi.

Wireline Drillstring for CCSDP. On request of the CCSDP the OSG developed and purchased in cooperation with the service industry a wireline coring drillstring with a depth capacity 5.5 km (640 pipes of 9 m length each). The drillpipe includes a complete downhole assembly with heavy weight collars (60 pipes of 9 m length each) producing with impregnated core bits a 157 mm diameter well. The mining type wireline coring string has three core barrels (6 m length) and produces nominally 94 mm diameter drillcores, which can be re-oriented through a gravity tool face.

Hammer Coring System. In the extremely hard UHP-metamorphic rock drilling in the Chinese CSDP, a new kind of coring method was applied from the depth of 100 m to more than 5100 m. The bottom-hole assembly of the new coring method consists of down-hole motor, a hydro-hammer, and a double tube core barrel. Another kind of coring tool, the so-called "three integrated" one, is a wire-line coring system consisting of downhole motor, hydro-hammer, and wire-line core barrel. Both systems were developed within the CCSDP in China and provided excellent results (30% higher rate of penetration per bit run) and allowed continuous coring with very high core recovery (88%).

Fig. 6. The Global Lake Drilling Facility GLAD800 on Lake Peten Itza in March 2006. The system consists of a barge of shipping containers and a small wireline drilling rig (photo by J. Kueck).

Hostile Environment Downhole Logging Tools. The OSG developed and purchased a basic set downhole logging instruments for in-situ geophysical measurements. The logging tool set is innovative as it combines two usually conflictive specifications: slimhole tool dimensions and hi-temperature/hi-pressure tool rating. The tools are smaller than 52 mm in diameter and work under ambient conditions of 150 °C and 80 MPa. These tools are based on conventional sonde techniques for slimhole shallow logging. To achieve the high ratings special solutions had to be implemented: the magnetic susceptibility tool got a completely new designed pressure resistent teflon-like housing around the sensors or the gamma ray detector had to deliver strong signals also at high temperatures and despite the small volume available.

Camera Image Scanner (CIS). The Camera Image Scanner (CIS) is a light-weight and easy to use optical scanner for slabbed or unrolled (360°) cores (Fig. 7). The system has been developed by an OSG outsourced company to provide at the drill site easily and inexpensive digital fotos. The device can also be used to make overview pictures of core boxes, cuttings and thin sections or other surfaces. In combination with the ICDP DIS the device can be used to build up virtual core archives. The included software package contains a special interface to communicate with the DIS, but it is also possible to use the scanner stand-alone. It has been used at, for example, the Taiwan Chelungpu drillsite and was applied at the Chesapeake Bay Crater drilling project.

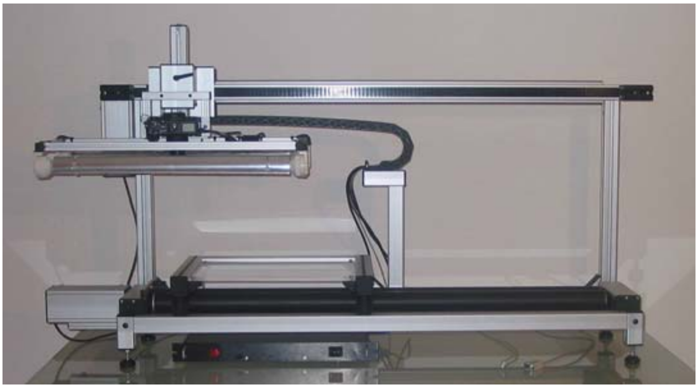

Fig. 7. Lightweight digital optical core image system with standard digital still camera and high precision step motors to scan up to 1 m long drillcores. A software system matches together the images of slabbed or of 360° unrolled core for documentation and archiving through the DIS (photo by Smartcube GmbH).

Strategies for High-Temperature Coring and Well Completion. The fundamental purpose of the Iceland Deep Drilling Project (IDDP) is to test the concept that producing supercritical high-enthalpy hydrous fluids in natural settings has economic benefits over producing conventional geothermal fluids. Modelling indicates that under favorable conditions, a 4-5 km deep well producing supercritical fluids at temperatures significantly greater than 450°C could yield sufficient high-enthalpy steam to generate 40-50 MW. That is an order of magnitude greater electrical power output than is usual from a conventional 2-km-deep well producing from a subcritical, liquid-dominated geothermal reservoir. The extreme temperatures expected during drilling and completion in the planned deep IDDP test well required a detailed investigations. Two ICDP workshops focused on these and related issued and led to a substantial technical feasibility study published by the IDDP.

The Unzen Volcano Drilling was facing a similar hurdle in the stage of the project development, because the modelled temperatures in the target depth within the active feeder dyke were estimated to range to up to 600° C if dry heat transfer would prevail. Therefore, a novel drilling strategy was developed by the Principal Investigators to drill and case with considerably enlarged diameters in order to allow for high mud circulation rates during drilling. These high flushing rates were planned to cool the formation temperatures down considerably. This concept helped also to stabilize the encountered very loose volcanic rubble formations with additional casings and use standard size Downhole motors.

Long-term Downhole Monitoring Tools and Strategies. A quasi-continuous temperature profile can be measured with high accuracy with fibre-optic distributed temperature sensing (DTS). For ICDP projects such as Hawaii the GFZ Potsdam used a temporary installation following wireline logging practice. However, for the Mallik gas hydrate project the GFZ Potsdam developed a permanent installation of the fiber-optic DTS cables. The sensor cables were attached with custom-built cable clamps during the installation of the borehole casings in all three Mallik wells. Data recordings were read out with a temporary set-up of the DTS surface equipment several days, two months, nine months and two years after the cable deployment. The data provided detailed temperature profiles and temperature gradients and were used to model drilling-induced thermal disturbance, equilibration processes and mobilization of latent heat during gashydrate decomposition.

An other application of fiber optic sensing was used in the Gulf of Corinth project were fiber Bragg grating (FBG) strain sensors were installed in a shallow borehole by the GFZ Potsdam. The permanent captors recorded the deformation of the borehole casing caused by the rift faulting mechanics in the Gulf of Corinth. The 100 m long permanent strain sensor setup consists of optical fiber strings with intrinsic FBG elements embedded force-fit on the outer casing surface. Parallel temperature logs served to discriminate strain and temperature induced Bragg wavelength shifts.

An innovative set of downhole monitoring tools (e.g., coiled-tubing conveyed seismometers) for the San Andreas Fault Zone Observatory at Depth (SAFOD) has already been developed for and tested in the Long Valley Exploration Well. However, the SAFOD will install after the completion of the sidetrack core-hole drilling in 2007, a permanent array for a monitoring period of 10 to 15 years. This array will consist of 5 stations of each 3-component geophones, 3-components accelerometer, and one tilt-meter, equally spaced by a 75 m - 100 m long rigid pipe. The bottom station of the array will also include a pressure and temperature gauge which will be positioned in one of the sidetrack holes and be sealed off from the rest of the hole with a casing packer above the sidetrack point. For maintaining roll angle orientation, the entire array will be installed pipe conveyed with cable and inflation lines leading to the surface. Clamping arms will be pointed to the high-side of the hole and ensure sufficient coupling to the casing of each station. The planning of the construction of the whole measurement line including the development of new sensors is organized and will be implemented by the OSG.

GFZ InnovaRig. Extensive experience with scientific drilling gained through the German Continental Deep Drilling Program (KTB) and through the operation of scientific drilling projects within the framework of the ICDP has shown that there is currently no drill rig available which has all the necessary technical equipment to satisfy the different scientific and technical requirements for deep scientific drilling projects.

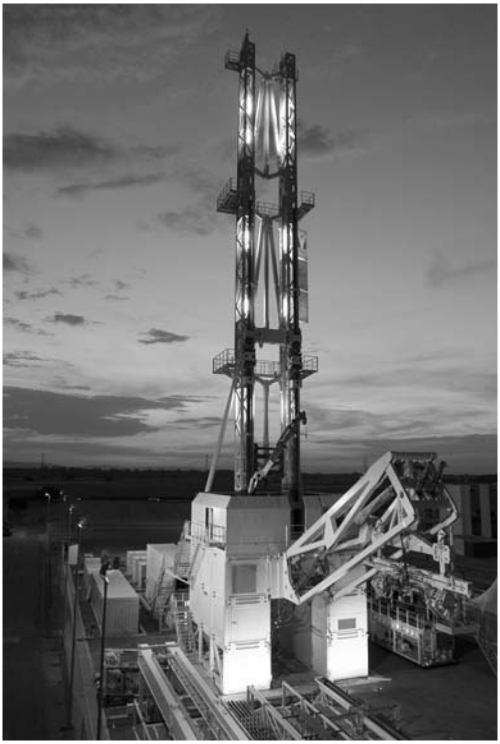

Fig. 8. Prototype of the InnovaRig (photo by Herrenknecht-Vertical GmbH).

There is, therefore, a “Research & Development” necessity for a drill rig which is flexible in its application, economic in its operation, and which can be employed for special missions. The technical concept for such rig has been defined for the research program of the Helmholtz Association of German Research Centers in the topics “Geosystems: the Changing Earth” and “Renewable Energies”. The main tasks are (1) the operational and scientific execution of ICDP projects, (2) drilling activities in connection with CO_2 sequestration, and (3) in the exploitation of geothermal resources.

This new research drill rig, named GFZ-InnovaRig (Fig. 8, Tab. 2), is meanwhile funded with a total investment sum of 15 Mio € to allow for reasonably-priced research drillings to a depth of approximately 5000 m. Furthermore, the development of new drilling technologies for scientific research drillings and other varied applications is planned. The rig will be owned by the GeoForschungsZentrum Potsdam and operated by a drilling contractor.

Table 2. Technical specifications of the InnovaRig

Drilling Depth	3.500 – 5.000 m
Regular Hookload	3500 kN
Nominal Rotary Speed	180 U/min; rpm
Rotary Torque	40 kNm – 75 kNM
Wireline Coring Speed	500 U/min; rpm
Wireline Coring Torque	12 kNm – 18 kNm
Tripping Speed	500 m/h; 500 m/hr
Hoist Cylinder Stroke	22 m
Drive Power up to	4000 kW
Rig Weight	approx. 370 tons
Mud Pumps	3 x 1.000 kW
Wireline Coring Mud Pump	1 x 350 kW
Mud Pressure	max. 350 bar
Mud Tank System	240 m³
Generator Set	3 x 1.540 kVA
Racking Capacity	> 7000 m
Wireline Coring Winch	5000 m, d=12,7 mm

InnovaRig has the following specifications:

- Compact modular construction for a minimization of drill-site size, reduction of transport costs, and minimal assembly time.
- High degree of automation for time and cost savings and highest levels of safety as well as environmental standards, e.g., pipe-handling system, automatic roundtrip equipment.

- Execution of standard drilling and coring procedures to a depth of approx. 5000 m and rig-specific preparation for the application of new technologies (e.g., casing while drilling, directional drilling, wireline coring, air lift drilling).
- Exceeding requirements for noise protection, safety and ergonomics.
- Preparation for the problem-free installation of special equipment for geoscientific investigations in the form of a “Mini-Field Laboratory”.

The rig concept, the rig construction and the rig operation are realized in close cooperation with an industry partner. It is planned to operate the rig in a shared use mode for research as well as for commercial drilling operations. The expected gains are considerably reduced day rates for scientific drilling projects while the operation for industry projects will provide higher fees for amortization of the investment.

4.2 Promotion of International Collaboration

It has been stated already at the Potsdam Conference in 1993 that any program of Continental Scientific Drilling that is established should try to develop close scientific and technological ties to the Ocean Drilling Program (ODP). This is most obvious in the area of research related to studying continental margins because they are situated in a gap between those areas normally considered in ocean drilling and in continental drilling. It is hoped that cooperation between ODP and ICDP can address many of the important scientific questions in this regions. However, there are also a number of other research themes where scientific cooperation between ODP and ICDP can provide complementary information, such as drilling the Chicxulub Impact Structure. Consequently, the ICDP from the very beginning has strived for a closer cooperation between both programs. The most important achievements are:

- Liaison memberships of ICDP and IODP representatives in panel and board meetings.
- Homogenization of proposal forms allowing for submission of the almost identical proposals to both programs.
- Joint ICDP-IODP project proposals, such as a new Chicxulub drilling proposal or the New Jersey off shore drilling proposal.
- Joint national and international meetings, such as the Euroforum meeting in Tromsö (2002) and Bremen (2004) or the annual joint IODP/ICDP DFG colloquia in Germany.
- Joint Town Hall Meetings at major conferences are conducted to bring together the community and exchange ideas.

- Co-operation in the Mission Specific Platform operations of IODP including for example the use of the ICDP Drilling Information System, (DIS) in the Arctic Coring Expedition 2004, on the Lomonosov Ridge, and the Tahiti Coral Reef Drilling.
- Jointly conducted international workshop on themes that are relevant to both programs.

The new journal entitled ”SCIENTIFIC DRILLING” which is jointly published by the IODP and ICDP, can be viewed as an important milestone towards a close scientific cooperation and consultation on thematic priorities and serves also as a joint outreach tool; see: http://www.icdp-online.de/scientific-drilling/.

Through its thematically-oriented research projects as well as through the requirement of establishing international science teams for each drilling project ICDP has also furthered the formation of new networks of scientific collaboration. One of the outstanding examples is the close cooperation between ICDP and the Past Global Changes Program (PAGES) in the field of paleoclimate and paleoenvironment. The availability of the GLAD800 has stimulated a PAGES group to develop a long-term scientific concept for paleoclimatic and paleoenvironmental studies in continental lakes world wide. Subprograms of PAGES, such as the International Decade of East African Lakes (IDEAL), actually formed their drilling proposals according to ICDP planning and integrated their mainly limnology- and biology-oriented program into the ICDP research theme “Earth History and Climate”. The Lake Malawi Drilling Project of ICDP conducted in 2005 was part of IDEAL.

5 Future Strategies and Science Plan

5.1 ICDP Conference “Continental Scientific Drilling 2005”

From March 30 to April 1, 2005, the 2nd Potsdam Conference on Continental Drilling was held at the GeoForschungsZentrum in Potsdam, with the title “ICDP - A Decade of Progress and Challenges for the Future”. This international conference at which 210 invited experts from 24 countries participated had two main objectives, first to present and summarize the main results obtained during the last eight years of ICDP Operations and second to identify and elaborate, in detail, main themes and key questions for future drilling activities on land. The scientific program focused on 8 major research areas:

1. Climate Dynamics and Global Environments

2. Impact Structures
3. Active Faulting and Earthquake Processes
4. The Geobiosphere
5. Volcanic Systems and Thermal Regimes
6. Natural Resources
7. Hotspot Volcanoes and Large Igneous Provinces
8. Convergent Plate Boundaries and Collision Zones

The conference was complemented by two workshops, one on “Drilling Technology”, at which representatives from the industry participated, and the second on the subject of “Education and Outreach” which was organized in cooperation with media representatives with the main aim of compiling the results of scientific drilling for use as school and training material as well as for presentation to the general public. Scientific papers on each of the eight thematic sessions compiled by the session conveners follow as chapters of this volume.

Acknowledgement

We would like to thank the contributors to the ICDP Conference in Potsdam in the year 2005, who provided a sound scientific reasoning for the future of continental scientific drilling.

Appendix: ICDP Drilling Projects

Lake Baikal Drilling Project

Summary

Lake Baikal is well-known as a magnificent sedimentary basin and a prime location for understanding fundamental processes involved in continental rifting and the evolution of lacustrine rift basins. Located in south-central Siberia, Lake Baikal is ideally positioned to test important paleoclimate models because the climate has the highest degree of continentality, the region has experienced no massive glaciation, and energy balance models show that the lake exhibits the highest degree of Milankovitch insolation variations.

Scientific drill cores and multichannel seismic demonstrate that numerous sites exist for recovery of continuous hemipelagic lacustrine sediments, that a robust geochronology can be developed for the Late Cenozoic at these sites, that the sediments exhibit high sensitivity to rapid paleoclimate and tectonic events. The main goal of the core investigations was to reconstruct high resolution Late Miocene-Pliocene climates and to shed new light on the biogeochemical evolution of Baikal in response to orogenic dynamics of East-Central Asia.

Principal Investigators and Science Team

Mikhail I. Kuzmin, Institute of Geochemistry, Irkutsk, Russia,
Douglas F. Williams, University of South Carolina, Columbia, USA,
Takayoshi Kawai, Japanese Association for Baikal Research, Tsukuba, Japan.
More than 100 scientists from four countries participated in the project.

Project Dates

Cores were recovered from December 1997 until April 1998

Operational Achievements

BDP-98 drilled on the Academician Ridge in the Central Lake Baikal to more than 600 m sediment depth in 380 m water depth (95% core recovery). The paleomagnetic stratigraphy correlates well to the BDP-96 record, thus providing an unparalleled opportunity for both long-term and high-resolution paleoclimatic reconstructions.

Key references

Sapota T, Aldahan A, Possnert G, Peck J, King J, Prokopenko A, Kuzmin M (2004) A late Cenozoic Earth's crust and climate dynamics record from Lake Baikal. Journal of Paleolimnology 32: 341-349, doi:10.1007/s10933-004-0195-9

Kashiwaya K, Ochiai S, Sakai H, Kawai T. (2001) Orbit related long-term climate cycles revealed in a 12-Myr continental record from Lake Baikal. Nature 410: 71–74

The Long Valley Exploration Well

Long Valley caldera in eastern California is one of several large calderas around the globe that have shown signs of magmatic unrest in the last several decades. Seismic unrest in the Long Valley Caldera in Eastern California has been characterized by recurring earthquake swarm activity and continued uplift of over 60 cm since 1979. The previously existing Long Valley Exploration Well resulted from a plan developed in the 1980's to drill to 6 km or 500°C in the centre of the resurgent dome in Long Valley caldera. The hole was to be used for engineering experiments related to energy extraction at near-magmatic temperatures.

Scientific goals of the project were to shed light on the nature of processes at mid-crustal depths in areas of active deformation by drilling into the seismogenic volume beneath the resurgent dome and 1) obtaining a complete core section for studies of the petrology, fracture state, and pore fluids; 2) determining the temperature profile below the hydrologic convective regime; 3) determining the state of stress within the seismogenic volume; and, 4) modelling present day hydrothermal conditions. In the long term, there was a strong interest in using the hole as a geophysical observatory with a number of down-hole instrument packages.

Principal Investigators and Science Team

David P. Hill, U.S. Geological Survey, Menlo Park, USA,
John H. Sass, U.S. Geological Survey, Flagstaff, USA,
John T. Finger, Sandia National Laboratories, USA.
About 60 scientists from 4 countries were cooperating in this project.

Project Dates

Drilling was executed from July until September 1998.

Project Achievements

Cores were retrieved from 2188 m depth to the final depth of 2997 m depth. The well served to conduct a set of commercial downhole logging operations and to test various instruments that measure seismicity, deformation, and fluid pressure. A new measurement with an instrument package about 27 m in length was installed at about 2300 m depth to convert the well into a geophysical observatory.

Key references

Fischer M, Röller K, Küster M, Stöckhert B, McConell VS (2003) Open fissure mineralization at 2600 m depth in Long Valley Exploratory Well (California): insight into the history of the hydrothermal system. Journal of Volcanology and Geothermal Research 127: 347-363

Hill DP, Dawson P, Johnston MJS, Pitt, AM, Biasi GP, Smith K (2002) Very-long-period volcanic earthquakes beneath Mammoth Mountain, California. Geophysical Research Letters 29, 1370, doi:10.1029/ 2002GL014833

Sorey ML, Hill DP, McConnell VS (2000) Scientific drilling in Long Valley Caldera, California; an update. California Geology 53: 4-11

Hawaii Scientific Drilling Project

Intraplate or "hot spot" volcanic island chains, exemplified by Hawaii, have played an important role in the understanding of plate tectonics, but in contrast to volcanism at convergent and divergent margins, the origin of intraplate volcanoes is not explained by the plate tectonic paradigm. The most widely held view of the origin of island chains is that they form from magma generated by decompression melting of localized, buoyant upwellings in the mantle. These upwellings, or "plumes," are believed to originate at thermal boundary layers in the mantle.

The study of hot spot volcanoes is impeded because the major volume of each volcano is inaccessible to sampling. Erosion typically exposes only a few hundred meters of the volcano's interior, out of a total thickness of 6 to 20 km. Continuous core drilling through a sequence of lavas on the flank of an oceanic volcano is the only way to sample its long-term history. From a sequence of core samples one can study variations in the petrology and geochemistry of erupted lava and changes in volcanic processes and structures over the one million year history of an oceanic volcano. The key point that motivates this project is that valuable information on mantle composition, processes, and structure can potentially be gained in an exquisitely systematic fashion through drilling.

Principal Investigators and Science Team

Donald J. DePaolo, University of California, Berkeley, USA,
Edward M. Stolper, California Institute of Technology, Pasadena, USA,
Donald M. Thomas, University of Hawaii, Honolulu, USA.
About 150 scientists from 7 countries are participating in the project.

Project Dates: Main drilling phase was performed from March to September 1999, the Second Drilling Phase with hole opening and cementing went on between April and June 2003, and the Third Drilling Phase with coring (3100 to 3340 m) was executed from October 2004 to February 2005.

Operational Achievements

Coring with 98% recovery to 3100 m in 1999 were performed with a commercial drilling rig and a purpose built a hybrid coring system. Another coring phase started in May 2003 after complex re-opening, casing, and cementing operations due to variable formation fluid pressures; coring operations started again in December 2004 and ended in February 2005 at 3340 m depth.

Key references

A series of papers have been published in AGU Journal “G-cubed” in 2003 to 2005 as “Theme”: Hawaii Scientific Drilling Project, Geochemistry, Geophysics, Geosystems, 2003 – 2005.

DePaolo DJ, Stolper E, Thomas, DM (2001) Deep drilling into a Hawaiian volcano. Eos, Transactions of the American Geophysical Union 82: 149, 154-155

Koolau Scientific Drilling Project

The subaerially exposed lavas of Koolau Volcano on the island of Oahu are geochemically distinct among Hawaiian shield lavas and are important to an understanding of the origin and evolution of the Hawaiian plume and the mantle because they appear to provide the strongest evidence for deep mantle recycling of oceanic crust. Recent studies of Koolau lavas in a new highway tunnel suggest that these geochemically distinct lavas may form only a thin veneer on the volcano.

Principal Investigator: Michael O. Garcia, University of Hawaii, USA.

Project Dates: Drilling was performed from April to June 2000.

Operational Achievements
The drilling operations with the GLAD 800 drilling rig allowed to recover 328 m of relatively unaltered core showing an interesting range of rock types (picritic basalts to pebbly sandstone). Analytical results confirm the distinct geochemistry hypothesis and the very small extent of Koolau volcano as skin deep only.

Key Reference
Haskins EH, Garcia MO (2004) Scientific drilling reveals geochemical heterogeneity within the Ko'olau shield, Hawai'i. Contributions to Mineralogy and Petrology 147: 162-188

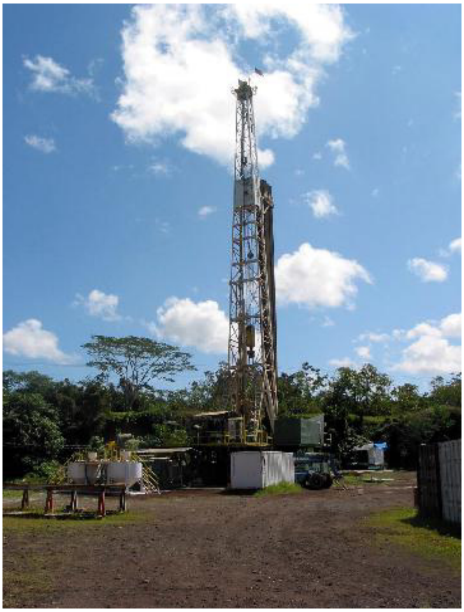

Fig 9. Photo of the drill-site and drill rig of the Hawaii Scientific Drilling Project

Lake Titicaca Drilling Project

Summary

Lake Titicaca provides a unique opportunity to study a continuous record of past climate in tropical South America. As the only large and deep freshwater lake in tropical South America, sediment accumulated continuously and rapidly in the deeper portions of the basin for at least a few hundred thousand years. By contrast, nearly all of the previously studied sedimentary records in the Amazon basin are discontinuous or of much lower resolution. Lake Titicaca is a reliable recorder of the climate of a large portion of tropical South America. Furthermore, changes in lake level are correlated with interannual to much longer timescale variability of the tropical and high-latitude North Atlantic. It has been demonstrated that the important climatic elements can be clearly deduced from the proxy records obtained in drill cores. It was planned to take advantage of the carbon isotopic monitor of lake level to produce a record of lake level variation at about 50 year resolution over the course of the record. This was used to yield a totally unprecedented record of tropical moisture coincident with the large-amplitude fluctuations of the global mean climatic state that characterized the late Quaternary.

Lake Titicaca is also well situated to receive volcanic ash from the adjacent active arc and provides an important record of volcanism and volcanic ashes essential for dating older sediments in the cores.

Principal Investigators and Science Team

Paul A. Baker, Duke University, USA,
Sherilyn Fritz, Lehigh University, USA,
Geoffrey A. Seltzer, Syracuse University, USA.
About 20 scientists from three countries cooperated in the program.

Project Dates: Drilling operations lasted from April to May 2001.

Operational Achievements

Three sites on Lake Titicaca were drilled with overlapping cores at each site. A total of 625 m of sediment was recovered. Site 1 is west of Isla del Sol in 141 m of water (72 m core depth). A thick deposit of sand and gravel prohibited deeper drilling. Site 2 is to the east of Isla del Sol in 235 m water depth (136 m subbottom). Site 3 is in the smaller Lago Huinaimarca sub-basin, where in 40 m of water a depth of 125 m subbottom was reached.

Key references

Baker P, Rigsby C, Seltzer G, Fritz S, Lowenstein T, Bacher N, Veliz C (2001) Tropical climate changes at millennial and orbital timescales on the Bolivian Altiplano. Nature 409: 698-701

Baker P, Grove M, Cross S, Seltzer G, Fritz S, Dunbar R (2001) The history of South American tropical precipitation for the past 25,000 years. Science 291: 640-643

Baker P (2002) Trans-Atlantic climate connections. Science 296: 67-68

Chinese Continental Scientific Drilling Project

One of the most exciting geologic discoveries in the last 20 years is the finding of the presence of a major ultrahigh pressure (UHP) metamorphic belt in the Dabie-Sulu region of eastern China. In this belt, high-grade continental crustal rocks contain both diamond and coesite and clear evidence of crustal subduction to depths >150 km. This belt formed by collision between the North China and Yangtze blocks in the Mesozoic between about 210 and 220 Ma.

A site in the Sulu segment of the belt where ultramafic rock and eclogite are hosted in coesite-bearing gneiss was selected for deep drilling to determine the three-dimensional structure, composition, and geophysical character of this convergent plate boundary; to investigate the nature and timing of the UHP metamorphism; to investigate the crustal dynamics anti-crust mantle interaction involved in the formation and exhumation of the UHP rocks; to study the processes of fluid circulation and mineralization the crust and upper mantle; to establish a long-term, natural laboratory for the study of crustal dynamics and the evolution of deep continental crust.

Principal Investigators and Science Team

Xu Zhiqin & Yang Wencai, Institute of Geology, Beijing, China. Cong Bolin, Academia Sinica, Beijing, China. Hartmut Kern, Kiel University, Germany. Roland Oberhänsli, Potsdam University, Germany. Bor-Ming Jahn, University of Rennes, France. Paul Robinson, Dalhousie University, Canada. David B. Rowly, University of Chicago, USA. Juhn G. Liou, Stanford University, USA.
More than 80 scientists are cooperating in the science team.

Project Dates: Drilling operations were going on for almost four years from July 2001 until March 2005.

Operational Achievements

A 2000 m deep pilot well was drilled until early May 2002; hole opening until end of August 2002 in order to use the pilot well as main well. The main well of the project was drilled to a final depth of 5158.0 m and completed on March 8, 2005. The holes were being continuously cored, with an average core recovery of 85%. A full suite of geophysical logs has been run, including gamma ray geochemistry, fluid, sonic, and vertical seismic profiling (VSP).

Key references

Zhang Z, Xiao Y, Hoefs J, Xu Z, Liou JG (2005) Petrogenesis of UHP metamorphic crustal and mantle rocks from the Chinese Continental Scientific Drilling Pre-pilot Hole 1, Sulu Belt, eastern China. International Geology Review 47: 1160-1177

Su S, Liou JG, You Z, Liang F, Zhang Z (2005) Petrologic study of ultrahigh-pressure metamorphic cores from 100 to 2000 m depth in the main hole of the Chinese Continental Scientific Drilling Project, eastern China. International Geology Review 47: 1144-1159

Chicxulub Scientific Drilling Project

The birth of the Chicxulub multiring impact basin approximately 65 million years ago represents one of the most dramatic events in Earth's history. A discrete layer of ejected dust, ash, and spherules is distributed worldwide at the Cretaceous-Tertiary boundary. Associated with this layer is evidence not only of its impact origin but also of global wildfires, global cooling, acid rain, and widespread death marking the end of the Mesozoic Era. Chicxulub is relatively young and because it formed in an area of active deposition, its interior morphology has been shielded from the effects of erosion and therefore, offers a unique opportunity to gather new and important constraints on the nature of such large multiring impact basins and how their formation affects geological and biological evolution.

It was determined that the primary coring goal of CSDP should be to recover a complete sequence of impact-generated rocks overlying the downfaulted Mesozoic target rocks from within the crater. Another important goal was to recover a continuous section through the Tertiary cover rocks above the impactites. Finally, it was hoped to penetrate into the upper part of the disturbed Cretaceous-Jurassic platform rocks below, in order to provide additional constraints on target-rock compositions and deformation styles.

Principal Investigators and Science Team

Jaime Urrutia Fucugauchi, Universidad National Autónoma de México,
Dante Morán-Zenteno Universidad National Autónoma de México,
Virgil L. Sharpton, University of Alaska at Fairbanks, USA,
Dieter Stöffler, Humboldt University Berlin, Germany,
Jan Smit, Free University of Amsterdam, Netherlands,
Richard T. Buffler University of Texas at Austin, USA.
About 130 scientists from 12 countries are cooperating in the CSDP.

Project Dates: Drilling Operations were conducted from December 2001 to February 2002.

Operational Achievements

From December 2001 to February 2002 the Project drilled a 1511 m deep well which was successfully cored from 392 m to 1500 m depth with 98.5% core recovery in 372 core runs. From 0 to 794 m depth Tertiary sedimentary strata of calcareous composition were crosscutted, impact rocks of six different layers were met between 794 and 895 m depth and from 895 m to 1511 m Cretaceous target rocks (rotated megablocks and interlayered injected dikes) could be recovered.

Key references

Two special issues with basic papers were published in June and July 2004 in Meteoritics and Planetary Science 39, issues 6 and 7.

Mallik Gas Hydrate Research Well

Natural gas hydrates represent an immense hydrocarbon resource underlying large portions of the world's arctic continental areas and continental shelves. An international consortium was formed to establish a world research site for the study of continental natural gas hydrates in the Mackenzie Delta of the northwestern Canadian Arctic. This site, the Mallik gas hydrate field, was discovered through an exploration well in 1971-1972. The project included a production research well and two nearby science observation wells.

The scientific and engineering research objectives for the production research well focus on two themes: (1) the assessment of the production and geotechnical properties of gas hydrates, and (2) an assessment of the stability of continental gas hydrates to climate change. Individual production tests were designed to isolate the reservoir response and collect a comprehensive and well calibrated production data set. In situ geothermal and geomechanical measurements, borehole and surface geophysical surveys, and a wide variety of laboratory studies on the recovered core were designed to complement the production-test program and carefully quantify the in situ reservoir properties. After the field program, numerical modelling studies were undertaken to analyze the test data and predict possible reservoir response to long-term production and climate change.

Principal Investigators and Science Team
Scott R. Dallimore, Geological Survey of Canada,
T.S. Collett, U.S. Geological Survey,
T. Uchida, Japan Petroleum Exploration Company,
Michael Weber, GeoForschungsZentrum Potsdam, Germany.
More than 250 scientists from 11 countries participated in the Mallik project.

Project Dates: Operational project phase: December 2001 to February 2002.

Project Achievements
The Mallik project achieved its technical goals very successfully and drilled three wells in 40 m distance to 1188 (observation wells) m and 1166 (production well) m depth, respectively. The latter was continuously wireline cored from 885 to 1151 m depth. Three main gas-hydrate bearing intervals at 852-930, 942-993, and 1070-1107 m depth were identified and extensively tested as planned. The base of the gas-hydrate stability zone was met at 1107 m depth. A large thermal-stimulation production test was carried out that stimulated a 13 m thick sand section with high gas saturation and allowed for flow volume quantification and seismic and thermal monitoring of geophysical parameters.

Key References
Since 2000, more than 50 papers have been published. A special volume has been published as Bulletin 585, Geological Survey of Canada, in 2005. The book comprises a summary of results and 63 individual papers.

Gulf of Corinth Rift Laboratory

The objective of the Corinth Rift Laboratory (CRL) is to integrate surface and downhole observations for a better understanding of the physics of faulting in an extensional tectonic regime, with special attention to interactions between fluids and active faults. The Corinth Rift is opening at a rate of 1.5 cm/year, with its southern shore uplifting at a rate close to 1 mm/year. It is one of the most seismically active zones in Europe.

The drill site for CRL is located in Aigion, a city on the southern shore of the Corinth Gulf, which was hit by a magnitude 6.5 earthquake in 1995. On this location, the drilling project aims at instrumenting a 1000 m deep borehole, which intersects the recently activated Aigion fault. Particular emphasis is placed on documenting the role of fluids on fault behavior and the role of earthquake faulting on regional hydrogeology thanks to the continuous downhole monitoring of various parameters characteristics of the fault fluid flow conditions.

Principal Investigators and Science Team
Francoise H. Cornet, Universite Paris, France,
Ioannis Vardoulaki, Technical University of Athens, Greece,
Günther Borm, GFZ Potsdam, Germany,
Efstathios Chiotis, Technical University of Athens, Greece.
62 scientists from 7 countries are cooperating in the project.

Project Dates: Operations for the deep hole in Aigion lasted from June to September 2002.

Operational Achievements
The borehole was drilled in a combination of Rotary Drilling and Wireline Diamond Coring technique in order to allow for both, a 12 ¼“ and 9 5/8“ drilling diameter (0 – 708.8 m) and high-quality coring in the fault section of the borehole (708.8 – 787.4 m, 101 mm core diameter). The relatively large diameter was chosen to enable later full instrumentation. Thirty core runs yielded 71% core recovery; the main fault zone was fully cored without any loss of material.

Key references

Cornet FH, Doan JML, Moretti I, Borm G (2004) Drilling through the active Aigion fault: the AIG10 well observatory. Comptes Rendus Geoscience 336: 395–406

Moretti I, Delhomme JP, Cornet F, Bernard P, Schmidt-Hattenberger C, Borm G (2002) The Corinth Rift Laboratory: monitoring of active faults. First Break 20: 1-7

San Andreas Fault Zone Observatory at Depth (SAFOD)

The San Andreas Fault Observatory at Depth (SAFOD) is a deep borehole observatory that will directly measure the physical conditions under which plate boundary earthquakes occur. SAFOD is designed to directly sample fault zone rocks and fluids, measure a wide variety of fault zone properties, and monitor a creeping and seismically active fault zone at depth. A 3.2-km-deep hole will be drilled through the San Andreas fault zone close to the hypocenter of the 1966 M~6 Parkfield earthquake, where the San Andreas fault slips through a combination of small-to-moderate magnitude earthquakes and aseismic creep. The drill site will be located sufficiently far from the San Andreas fault to allow for drilling and coring deviated holes through the fault zone starting at a vertical depth of about 3 km and continuing through the fault zone until relatively undisturbed country rock is reached on the other side.

Even after decades of intensive research, numerous fundamental questions about the physical and chemical processes acting within the San Andreas and other major plate-bounding faults remain unanswered. SAFOD will provide new insights into the composition and physical properties of fault zone materials at depth, and the constitutive laws governing fault behavior. It also will provide direct knowledge of the stress conditions under which earthquakes initiate and propagate. Although it is often proposed that high pore fluid pressure exists within the San Andreas fault zone at depth and that variations in pore pressure strongly affect fault behavior, these hypotheses are unproven and the origin of overpressured fluids, if they exist, is unknown. As a result, a myriad of untested and unconstrained laboratory and theoretical models related to the physics of faulting and earthquake generation fill the scientific literature. Drilling, sampling and downhole measurements directly within the San Andreas fault zone will substantially advance our understanding of earthquakes by providing direct observations on the composition, physical state, and mechanical behavior of a major active fault zone at hypocentral depths. In addition to retrieval of fault zone rock and fluids for laboratory analyses, intensive downhole geophysical measurements and long-term monitoring are planned within and adjacent to the active fault zone. Observatory-mode monitoring activities will include near-field, wide-dynamic-range seismological observations of earthquake nucleation and rupture and continuous monitoring of pore pressure, temperature, and strain during the earthquake cycle.

Directly evaluating the roles of fluid pressure, intrinsic rock friction, chemical reactions, in situ stress and other parameters in the earthquake process will provide opportunities to simulate earthquakes in the laboratory and on the computer using representative fault zone properties and physical conditions.

Principal Investigators and Science Team

Mark D. Zoback, Stanford University, USA,
William S. Ellsworth, U.S. Geological Survey, USA,
Stephen Hickman, U.S. Geological Survey, USA.
More than 100 scientists from 7 countries are participating in SAFOD.

Project Dates: The pilot well was drilled in summer 2002; the main well, phase 1 **was done** in 2004, and phase 2 was performed in summer 2005.

Operational Achievements

The pilot well was drilled successfully from June 12 to July 24, 2002 according to plan.

The Phase 1 main hole was drilled and cored as planned. Due to a wrong directional measurement of a service company the pilot well was truncated and the seismic string destroyed below 1100 m depth; however the well was repaired in the beginning of the 2005 operational campaign. The fluid sampling was postponed due to a lack in fluids.

Phase 2 achieved its major goal: the truncation and sampling of the San Andreas Fault Zone and the safe casing of the instable zone. However, minor reduction in operational goals were necessary due e.g. to borehole instabilities causing cut downs in logging-while drilling and higher cementation costs or risky packer operations during final hydrofrac experiments. A final rotary drilling depth was reached on August 9 at 3987 m drillers depths.

Key References

A special issue of Geophysical Research Letters 31 is summarized in:

Hickman S, Zoback M, Ellsworth W (2004) Introduction to special section: Preparing for the San Andreas Fault Observatory at Depth. Geophysical Research Letters 31, L12S01, doi:10.1029/2004GL020688

Zoback M (2006) SAFOD Penetrates the San Andreas Fault. Scientific Drilling 2: 32-33, doi:10.2204/iodp.sd.2.07.2006

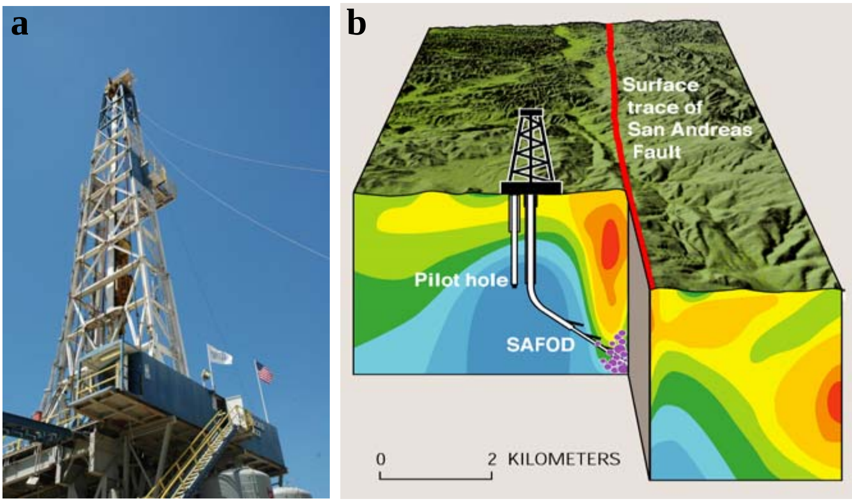

Fig. 10.a. SAFOD drill rig. **b.** Block diagram showing the San Andreas Fault and SAFOD drilling location at Parkfield, California.

Unzen Scientific Drilling Project

The volcanic eruptions at Unzen (Japan) during 1990-1995 took a heavy toll on life and property through devastating pyroclastic flow events. In order to understand the structure and growth history of the volcano and to clarify the eruption mechanisms of SiO_2-rich viscous magmas, a six-year project consisting of two phases, was started in April 1999. In the first phase, two holes were drilled into the volcano's flank. In the second phase, drilling penetrated the magma conduit that fed a lava dome at the summit.

The magma conduit, especially its upper part, is believed to be the site of effective degassing that is the major factor controlling eruption styles. The pressure-dependent nature of solubility of volatiles, principally water, accelerates vesiculation as magma approaches the service and produces geophysical signals (earthquakes and inflation) in the shallow conduit region. Drilling into this region allowed for the first *in situ* observations and sampling of a still-hot conduit and wall rocks of a recent, well-observed eruption.

Principal Investigators and Science Team
Setsuya Nakada, University of Tokyo, Japan,
Kozo Uto, Geological Survey of Japan, Tsukuba, Japan,
John C. Eichelberger, Geophysical Institute, University of Alaska, USA,
Hiroshi Shimizu, Institute of Seismology, Kyushu University, Shimabara, Japan.
28 scientists form 4 countries are participating in the USDP.

Project Dates: The project was executed in three phases over the years 2002 to 2004, with the main drilling phases during summers 2003 and 2004.

Operational Achievements
During drilling operations, total loss of mud circulation, wall collapse, and accidental deviations of well trajectory occurred frequently. It was decided to use aerated drill mud, enhanced water supplies, and the use of a top-drive system. With orientation controlled by electromagnetic measurement while-drilling technique, the well reached its maximum, planned inclination of 75° at 794 m depth. The drilling target was revised based on re-analysis of seismic and geodetic. Drilling operation in 2004 advanced faster than planned and after a casing setting at 1,550 m, drilling was carried out with spot coring and logging. The conduit region was reached near sea level (about 2,000 m drilled depth, ca. 1.3 km vertically below the crater). The drilling operation was terminated at the end of July 2004, leaving USDP-4 cased down and plugged to the 1,550 m, for further operations.

Key References
Nakada S, Eichelberger J (2004) Looking into a volcano; drilling Unzen. Geotimes 49: 14-17

Nakada S, Uto, K, Sakuma S, Eichelberger JC, Shimizu, H (2005) Scientific results of conduit drilling in the Unzen Scientific Drilling Project. Scientific Drilling 1: 18-22, doi:10.2204/iodp.sd.1.03.2005

Taiwan Chelungpu Fault Drilling Project (TCDP)

The 1999 Chi-Chi, Taiwan earthquake (Mw 7.7) produced spectacular surface faulting with vertical displacements of up to 8 m on the Chelungpu fault. The rupture behavior of this earthquake was well recorded by the Taiwan Strong Motion recorders, teleseismic data, and GPS measurements. To understand the earthquake rupture process, one of the main issues is the level of stress on the fault before, during, and after the earthquake. The energy balance between the tectonic stress, dynamic friction, radiated energy, and heat dissipation controls the character of the dynamic rupture. There are many hypotheses for how a fault loses strength during sliding, including slip weakening, dilatational slip pulses, thermal pressurization, mechanical lubrication, and melting to name a few. Physical data is critical needed to make progress in understanding how large earthquakes occur. The Chelungpu-fault project successfully obtained physical samples of the fault where large displacements occurred, was capable to measure the physical properties and mechanical behavior of the rocks above and below the fault zone and thoroughly documented the state of stress in these rocks following such a large slip event.

Principal Investigators and Science Team

Kuo-Fong Ma, National Central University, Taiwan,
Yi-Ben Tsai, National Central University, Taiwan,
Mark D. Zoback, Stanford University, USA,
Stephen Hickman, US Geological Survey, USA,
Hisao Ito, GSJ/AIST, Japan,
Wonn Soh, JAMSTEC, Japan.
More than 100 scientists from 6 countries are participating in the TCDP.

Project Dates

Drilling started in January and ended December 2004.

Operational Achievements

The well was drilled to 430 m depth in rotary mode and cored down to 2003 m depth with continuous wireline coring as projected. The fault zone was penetrated at approximately 1200 m to 1500 m depth.

Key References

Ma KF, Tanaka H, Song SR, Wang CY, Hung JH, Tsai YB, Mori J, Song YF, Yeh EC, Soh W, Sone H, Kuo LW, Wu HY (2006) Slip zone and energetics of a large earthquake from the Taiwan Chelungpu-fault Drilling Project. Nature, in press

Hirono T, Ikehara M, Otsuki K, Mishima T, Sakaguchi M, Soh W, Omori M, Lin W, Yeh E, Tanikawa W, Wang C (2006) Evidence of frictional melting within disk-shaped black materials discovered from the Taiwan Chelungpu fault system. Geophysical Research Letters 33, L19311, doi:10.1029/2006GL027329

Lake Bosumtwi Drilling Project

The Bosumtwi impact crater in Ghana is almost completely filled by Lake Bosumtwi with a rim-to-rim diameter of about 11 km, while the lake has a diameter of about 8 km and maximum depth of about 80 m. The crater has an age of 1.07 Ma and was excavated in lower greenschist facies metasediments of the 2.1-2.2 Ga age. Recent detailed geophysical studies provided a detailed image of the crater structure. A shallow drilling project studied the near-surface composition of impact rocks. High-resolution seismic studies led to the discovery of a sediment-covered central uplift. Some shallow cores of lake sediments were also recovered.

Deep drilling was desirable 1) to obtain a complete 1 million year paleoenvironmental record and 2) to study the subsurface structure and crater fill of one of the best preserved large young impact structures. Bosumtwi is in a perfect location to reconstruct and investigate interannual through orbital-scale variations in i) the West African monsoon, ii) hydrologic variations of the Sahel, iii) dust export from SW Africa, and iv) sea-surface temperature variations in the tropical East Atlantic. Bosumtwi is one of only two known young craters of this size, and may have a crucial diameter at the changeover between a traditional “complex” crater with a central peak and a crater structure that has a central peak-ring system. Drilling allowed to correlate geophysical studies and provided material for geochemical and petrographic correlation studies between basement rocks and crater fill.

Principal Investigators and Science Team

Christian Koeberl, University of Vienna, Austria,
Bernd Milkereit, University of Toronto, Canada,
Christopher A. Scholz, Syracuse University, USA,
Jonathan T. Overpeck, University of Arizona, USA.
More than 60 scientists from 8 countries are members of the science team.

Project Dates and Operational Achievements

Eight sites including six sediment legs and two impact wells were drilled and approximately 2100 m cores were retrieved in the operational phase. At six sediment locations up to 300 m long cores and at two impact sites 451 and 545 m deep wells were drilled successfully July to October 2004.

Key references

Koeberl C, Peck J, King J, Milkereit B, Overpeck JT, Scholz CA (2005) The ICDP Lake Bosumtwi Drilling Project: A first Report. Scientific Drilling 1: 23-27, doi:10.2204/iodp.sd.1.04.2005

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Lake Malawi Drilling Project

The top scientific objective of the project was to obtain a continuous, high-resolution (annual-decadal) record of past climates in the continental tropics over the past ~800 kyr. Other primary scientific objectives of the drilling program intersect several fields, including extensional basin evolution and neotectonics, evolutionary biology, and the environmental background to human origins.

The project is an integrated scientific drilling campaign and analytical laboratory effort. Lake Malawi has long been recognized as an outstanding laboratory and archive for the study of tropical paleoclimatology, extensional tectonics, and evolutionary biology. Along with Lake Tanganyika, Lake Malawi holds the promise of a high-resolution paleoclimate record of unparalleled antiquity in the continental tropics. The critical role of the tropics in driving global circulation is widely recognized, but the climatic linkage between tropical Africa and the high latitudes at decadal-centennial through orbital timescales, has yet to be established.

Principal Investigators and Science Team
T.C. Johnson, University of Minnesota-Duluth, USA,
C.A. Scholz, Syracuse University, USA,
A.S. Cohen, University of Arizona, USA,
M.R. Talbot, University of Bergen, Norway,
E. Odata, Univ. of Nairobi, Kenya,
M. Dolozi, University of Malawi,
L. Kalindekafe, Department of Mines, Malawi,
J.J. Tiercelin, Universite de Bretagne Occidentale, France.
More than 30 scientists from 9 countries are cooperating in the project.

Project Dates: Operations were performed in February and March 2005.

Operational Achievements
A total of 623 m of core samples were recovered from below the lakebed's surface. At a site in the far north, the project drilled three holes in water depths of 350 m and collected sediment samples to a depth of 40 m, representing about 100,000 years. In central Lake Malawi, where the water depth is 600 m, the project drilled four holes, the deepest of which extended 378 m below lake bottom. At this site, the oldest sediment samples collected are approximately 1.5 million years in age.

Key references
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Scholz CA, Cohen A, King J, Johnson TC, Lyons RP, Talbot MR (2006) Scientific Drilling on Lake Malawi: A long, high-resolution record of climatic and limnological change from southern tropical East Africa. Geological Society of America, Abstracts 38, 7, 83

Drilling Active Faults in South African Mines

The physics of earthquake processes has remained enigmatic due partly to a lack of direct and near-field observations that are essential for the validation of models and concepts. DAFSAM proposes to reduce significantly this limitation by conducting research in deep mines that are unique laboratories for full-scale analysis of seismogenic processes. The mines provide a 'missing link' that bridges between the failure of simple and small samples in laboratory experiments, and earthquakes along complex and large faults in the crust. There is no practical way to conduct such analyses in other environment. To unravel the complexity of earthquake processes, this project is designed as integrated multidisciplinary studies of specialists from seismology, structural geology, mining and rock engineering, geophysics, rock mechanics, geochemistry and geobiology. The scientific objectives of the project are the characterization of near-field behavior of active faults before, during and after earthquakes.

Principal Investigators and Science Team

Ze'ev Reches, University of Oklahoma, USA,
Yehuda Ben-Zion, USC, USA,
Tom Dewers, University of Oklahoma, USA,
Malcolm Johnston, USGS, USA,
Thomas Jordan, USC, USA,
Hiroshi Ogasawara, Ritsumeikan University, Japan,
Ewan Sellers, CSIR-Miningtek, Johannesburg, ZA,
Steve Spottiswoode, CSIR-Miningtek, Johannesburg, ZA,
Gerrie van Aswegen, ISSI, Carletonville, ZA,
Sue Webb, Wits University, Johannesburg, ZA,
Mark Zoback, Stanford University, USA.
About 60 scientists from 6 countries are participating in DAFSAM.

Project Dates: Project operations started in April 2005.

Key Reference

Reches Z and the DAFSAM and NELSAM teams (2006) Building a natural earthquake laboratory at focal depth (DAFSAM-NELSAM project, South Africa). Scientific Drilling 3: 30-33, doi:10.2204/iodp.sd.3.06.2006

Iceland Deep Drilling Project

The IDDP aims to investigate the deeper levels of hydrothermal systems and to determine if utilizing supercritical fluids could increase power production from existing high-temperature geothermal fields by a factor of 5-10. The objectives of the 3.7 km deep geothermal well at Reykjanes are to investigate:

- Volcanic geology and formation of sheeted dike complexes.
- Mid-ocean rifting.
- Heat transfer from magmatic heat sources to hydrothermal systems.
- The environment of natural supercritical phenomena.
- Deep permeable convection cells in natural hydrothermal systems.
- Water-rock reactions during active hydrothermal alteration.
- Technical problems of drilling, well completion and logging and downhole sampling tools in hot hostile environments.
- Scientific, economic, and educational spin-offs worldwide, wherever high-temperature geothermal resources exist.

The first phase of coring will allow sampling fluids from 2.5 km and 3.7 km and produce 1.2 km of core from a high-temperature hydrothermal system located in an ophiolite-like environment that is actively forming today.

Principal Investigators and Science Team
G. O. Fridleifsson, Reykjavik, Iceland,
W A. Elders, Riverside, CA, USA.
More than 100 scientists from 9 countries are planning to participate.

Project Dates: A pilot coring experiment was executed in April 2005; the main project is planned for 2006 until 2008.

Operational Achievements
A first coring test was performed successfully in the 2250 m deep well on Reykjanes.

Key reference
Fridleifsson GO, Elders WA (2005) The Iceland Deep Drilling Project: a search for deep unconventional geothermal resources. Geothermics 34: 269-285

Lake Qinghai Drilling Project

The sedimentary record of the Lake Qinghai on the NE Tibetan Plateau reflects a long climatic and tectonic history for this environmentally sensitive region. The sediment records of the lake are examined, focusing on three time frames: 1) the long, full record, which may extend through the Pliocene and into the late Miocene, thereby providing insight about the inter-relationship of tectonism and monsoon climate; 2) the last ca. 130,000 years, an interval encompassing the last full glacial-interglacial cycle; 3) the last 2000 years, when the influence of human activity on climate variation and environmental change becomes especially pronounced.
The main scientific objectives of the drilling project are:

- To obtain an improved understanding of the late Cenozoic environmental history of the Lake Qinghai region and the development of the East Asian monsoon climate;
- To understand the Late Cenozoic tectonic evolution of the Lake Qinghai basin and the growth of the northeastern margin of the Tibetan Plateau and its effects on regional climate; and
- To correlate environmental records with other regional and global paleoclimatic records to obtain a better understanding of the connection between regional climatic change, the development of East Asian monsoon system, prevailing Westerlies, and, ultimately, the evolution of global climate.

Principal Investigators and Science Team
An Zhisheng, Institute of Earth Environment, Qi'an, China,
Steven Colman, University of Minnesota, USA,
Gerald Haug, GFZ Potsdam, Germany,
Peter Molnar, University of Colorado at Boulder, USA,
Takayoshi Kawai, Nagoya University, Japan.
About 60 scientists from 5 countries are participating in the project.

Project Dates: Coring operations were executed in August and September 2005.

Achievements
A total of 548 m sediment has been drilled at five sites with 323 m total core length (59 % recovery). The cores are shipped to Xi´an during fall 2005 for opening, sampling, and distribution for detailed analyses.

Key Reference
An Z, Ai L, Song Y, Colman SM (2006) Lake Qinghai Scientific Drilling Project. Scientific Drilling, 2: 20-22. doi:10.2204/iodp.sd.2.05.2006

Chesapeake Bay Drilling Project

The late Eocene Chesapeake Bay impact structure is among the largest and best preserved impact craters on Earth. Research topics include studies of impact processes, regional basin evolution (comparing impact effects with “normal” effects produced by tectonics, global sea-level, and sediment supply on a passive continental margin), hydrogeology, borehole and regional geophysics, and the deep biosphere. The subsurface structure of the Chesapeake Bay crater is constrained by several shallow coreholes, marine seismic-reflection surveys, and gravity analyses. Major subdivisions of the structure are a circa 38-km-diameter central crater enclosed by a 24-km-wide annular trough. Several characteristics make the Chesapeake Bay structure unique among subaerial and submarine impact craters on Earth. The goal of the project is to drill a 2.2-km-deep corehole near the central uplift within the “moat” of the structure’s central crater, to obtain as thick and undisturbed a post-impact succession as possible, and a thick section of impactites, and to reach the sub-crater basement to study the shock barometry and fracturing of these rocks.

Drilling in the central Chesapeake Bay crater provides important constraints on cratering processes in multi-layered marine targets in general and for comparison with results from the larger Chicxulub crater, in particular. The drilling will provide unique constraints on (1) the crater structure, depth, morphology, and formative processes, and (2) the crater materials, including impactite and basement lithologies, stratigraphy, mineralogy, chemistry, fractures, and physical properties, and (3) numerical models of impact processes. The project started in September 2005.

Principal Investigators and Science Team
Gregory S. Gohn, U.S. Geological Survey, Reston, USA,
Christian Koeberl, University of Vienna, Austria,
Kenneth G. Miller, Rutgers University, USA,
Wolf Uwe Reimold, University of the Witwatersrand, South Africa.
About 60 scientists from 7 countries participate in the project.

Project Dates: Drilling was performed from September 2005 to May 2006.

Key References
Gohn GS, Koeberl C, Miller KG, Reimold WU (2006) Chesapeake Bay Impact structure deep drilling project completes cores. Scientific Drilling 3: 34-37, doi:10.2204/iodp.sd.3.07.2006

Gohn GS, Koeberl C, Miller KG, Reimold WU, Cockell CS, Horton JW Jr, Sanford WE, Voytek MA (2006) Chesapeake Bay impact structure drilled. EOS, Transactions of the American Geophysical Union 87: 349, 355

Lake Peten Itza Drilling Project

Polar ice cores provide high-resolution records on both glacial-to-interglacial and millennial timescales of past climate change. Paleoclimatologists and climate modelers have focused increasingly on the tropics, however, as a potentially important driver of global climate change because of the region's role in controlling the Earth's energy budget. Tropical climate change is often expressed most strongly as variations in precipitation, and closed-basin lakes are sensitive recorders of the balance between precipitation and evaporation. Recent advances in drilling technology now offer the paleolimnological community the opportunity to obtain long sediment records from lowland tropical lakes e.g., in Central America. The search for an appropriate lake to study succeeded in 1999 when a bathymetric survey of Lake Petén Itzá, northern Guatemala, revealed a maximum depth of 165 m, making it the deepest lake in the lowlands of Central America containing a continuous history of lacustrine sediment deposition. A seismic survey of Lake Petén Itzá showed a thick sediment package overlying basement, with several subbasins containing up to 100 m or more of sediment suitable for drilling and comprising a high-resolution paleo-environmental archive.

Principal Investigators and Science Team
David A. Hodell, University of Florida, Gainesville, USA,
Flavio S. Anselmetti, ETH Zürich, Switzerland,
Mark B. Brenner, University of Florida, Gainesville, USA.
About 60 scientists from 7 countries are participating in the project.

Project Dates: Coring operations took place in February and March 2006.

Project Achievements
Cores were recovered from seven drillsites according to the original plans; six of these sites were triple cored to ensure full continuous coverage of the total section. . Water depths ranged from 30 to 150 m, and core length was 16 to 133 m with an average core recovery of about 93%. Shallow-water facies consist primarily of carbonate-rich sediment with abundant shell material, gypsum sand, and indurated gypsum crusts. Deep-water facies consist of diatom-rich, gray to brown clay that was deposited during lake highstands. The Petén Itzá Scientific Drilling Project achieved all of its field objectives and recovered 1327 m of high-quality core at seven sites. Preliminary results with respect to sediment lithology, density, magnetic susceptibility, and downhole natural gamma logs display a high degree of climate related variability that can be correlated among sites.

Key reference
Hodell D, Anselmetti F, Brenner M, Ariztegui D, PISDP Science Party (2006) The Lake Petén Itzá Scientific Drilling Project. Scientific Drilling 3:25-29, doi:10.2204/iodp.sd.3.02.2006

Climate Dynamics and Global Environments: A Community Vision for the Next Decade in ICDP

Julie Brigham-Grette[1], Gerald H. Haug[2],
and the Climate Working Group*

[1]Department of Geosciences, University of Massachusetts, Amherst, MA 01003, USA
e-mail: juliebg@geo.umass.edu (corresponding author)

[2]GeoForschungsZentrum Potsdam, Telegrafenberg C 324, 14473 Potsdam, Germany

Abstract

Today's provocative transformation of the Earth's climate system provides timely scientific impetus to an array of paleolimnological studies aimed at understanding natural climate variability vs. anthropogenic-induced change on global and regional scales. Continental drilling to acquire long paleoclimate records from a strategic network of sites is essential to documenting regional hydrologic and climatic responses to atmospheric change, providing a record that is key to resolving climate dynamics at fine spatial scales relevant to both climate modeling and societal impacts of climate change. An in-depth scientific assessment of natural climate variability based on lake drilling will also allow us to close huge gaps in our knowledge on the impact of climate change on the continental landscape and its ecosystems, vegetation and other biota, and ultimately the human environment. The scientific returns from lake drilling include, e.g., data needed to assess the environmental context of early human evolution,

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* Climate Working Group is: Paul Baker (Duke University, USA), Andy Cohen (University of Arizona, USA), Steve Colman (University of Minnesota-Duluth, USA), Pierre Francus (University of Quebec, Canada) Sherilyn Fritz (University of Nebraska, USA) Scott Lamoureu (Queen's University, Canada), Dennis Nielsen, DOSECC, USA), John Peck (University of Akron, USA), Lindsay Powers (University of Minnesota-Duluth, USA), Jim Russell (Brown University, USA), Moti Stein (Hebrew University of Jerusalem, Israel), Dirk Verschuren (Ghent University, Belgium), Stephan Vogel (Northern Illinois University, USA), Bernd Zolitschka (University of Bremen, Germany).

knowledge of paleoseismicity, natural hazard frequency, paleohydrology, and drought. Core scanning technology and other emerging proxy developments continue to propel international standards for initial core processing and storage ensuring the maximum investment return on studies of past continental and environmental change.

1 Motivation and Societal Relevance

Climate matters. The Earth's climate system has demonstrably changed on both global and regional scales since the pre-industrial era, with some of these changes attributable to human activities (IPCC 2001). Further amplified global warming since the 1970s, a rising sea level, regional climate shifts, and extreme climate events are now severely impacting the human habitat. We have an obligation to conduct research that provides a mechanistic understanding of present and past variations in regional and global climate. Of greatest concern regarding the human perturbation of climate is not what we know but rather what we do not know. While some changes are likely to be milder than expounded in the popular press, there are others that may be more severe than currently anticipated.

The inherent characteristics of climate change are critical to modern humanity. It is likely that human society, or at least large parts of it, could survive a *gradual* shift in climate. Perhaps a somewhat smaller fraction is prepared for the recurrence of multi-year extreme climate events. However, it is highly uncertain that much of human society could bear both types of change at once, a gradual change in the background state combined with repeated extreme climate events – the ability to survive and then recover from the extreme events would be greatly compromised. While a variety of technologies improve our situation relative to ancient civilizations, we are disadvantaged by current trends in population growth and by our own influence on climate. It is intriguing to consider how the World's populace will fare in the face of human-driven climate variability. In this light, population growth and the anthropogenic accumulation of greenhouse gases will likely be complementary contributors to future human crises, as climate affects the most fundamental human needs. It is the Third World where economic growth and demand for resources are fastest, and where a high proportion of humanity is most susceptible to climate change.

Most of the last 200 ka, which roughly bracket the rise of *Homo sapiens*, have been characterized by ice ages and climate instability. From this perspective, it may be that the inventiveness and collaboration of individuals and small groups of humans allowed for survival of the species in the face of scarce resources and environmental change. The rise of complex human civilizations began only over the last 10 ky of the current interglacial period, a time that, relative to at least the last 400 ky, is perhaps unprecedented in its climatic stability. This long delay between the rise of humans and the rise of advanced human civilizations may indicate that large, permanently settled human communities are not compatible with the vagaries of environmental change.

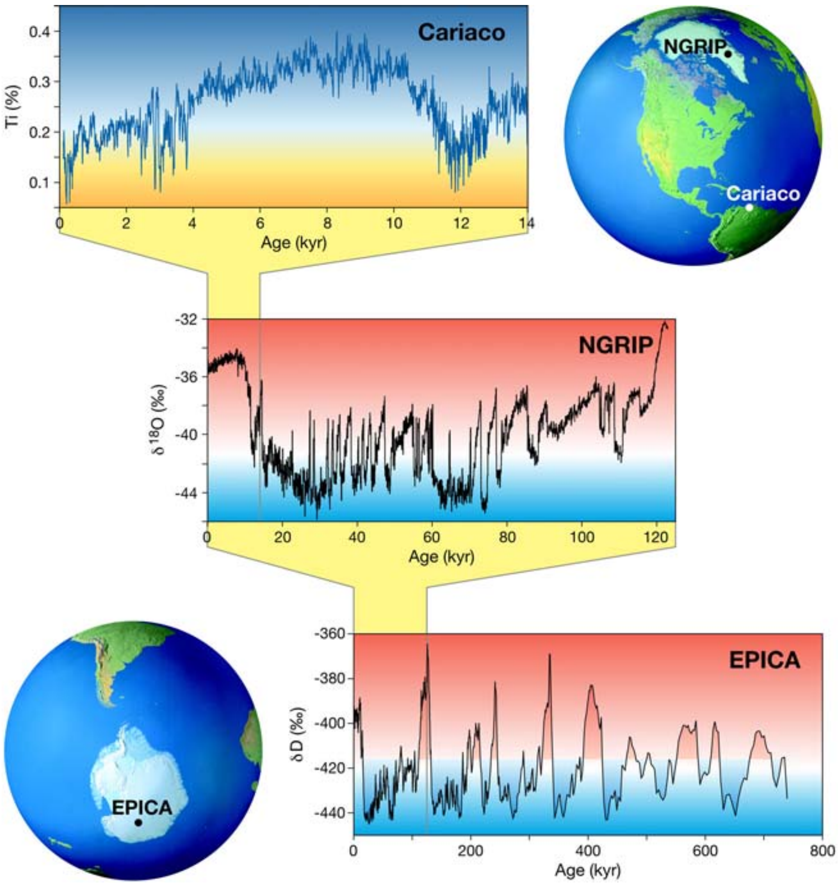

Fig. 1. Evidence for rapid global climate change at different timescales. Top: Wet-dry periods during the Holocene as documented by titanium concentrations in the Cariaco basin (Haug et al. 2001). Center: Large-amplitude millennial-scale climate variations during the last glacial period as reflected in oxygen-isotope values from the NGRIP ice core from Greenland (2004). Bottom: Climate change at orbital timescales from deuterium isotope measurements on the EPICA ice core drilled in Antarctica (EPICA community members 2004).

Climate reconstructions from ice cores, tree-rings, high-resolution ocean and lake-sediment cores, and speleothems now make it clear that climatic shifts have also occurred within the Holocene, in partly externally triggered by changes of the Earth´s orbit and by the variability of solar activity. These changes often coincided with the twists and turns of human history, including the rise of literate civilizations over the past 5,000 years. This suggests a strong connection between environment and the progress and fate of human civilization. However, the temporal resolution in available paleoclimatic records still represents a major limitation in the development of a globally meaningful view of Holocene climatic changes, their mechanisms, and their exact relevance to human history. Therefore, we need to develop a progressively more precise view of the past millennia. We see as one of our central missions the extraction of climate records from terrestrial (lacustrine sediments and tree rings) and marine archives at all temporal resolutions, centennial to seasonal, that are relevant to human society. The integration of these different types of archives will be a cornerstone of our strategy towards an improved regional view on climate change impacts. Given our research record, expertise, and facilities, we are in a unique position to make pioneering contributions in this area.

The human-driven accumulation of carbon dioxide and other greenhouse gases (e.g., methane and nitrous oxide) in the atmosphere will likely be one of the most pervasive environmental problems of this century. In a 'business as usual' scenario, driven by, among other things, the quest for an improved quality of life in the Third World, we are on track to raise the CO_2 content of the atmosphere to at least 800 ppm by the end of the century. To further our mechanistic understanding of critical thresholds in the climate system in the specific context of greenhouse gases, we need to find multiple natural experiments in the sometimes distant past that contain appropriate variations in greenhouse gas forcing. The variations in carbon dioxide, methane and nitrous oxide that are associated with the waxing and waning of ice ages provide an ideal platform for this work. Thus, we must strive to extend our pursuit of high-resolution records from continents and oceans to times preceding the current interglacial. Here, we can learn from past climates; however, it is also crucial to monitor ongoing changes such as sea level rise and shifts in climate zones. These data will help to ground-truth physical models and to gain an integrated knowledge of the highly sensitive climate system in a rapidly changing Earth, its external drivers and internal amplifiers and thresholds.

An in-depth scientific assessment of natural climate variability based on lake drilling will also allow us to close huge gaps in our knowledge on the impact of climate change on the continental landscape and its ecosystems, vegetation and other biota, and ultimately the human environment. The grand challenges are (*i*) to describe climate variability at an unprecedented temporal resolution and at a global scale during times of rapid climate change through the late Quaternary, and (*ii*) to gain a physical understanding of the reconstructed climate change by quantifying environmental change. Specific research goals include:

- To understand the variability of and the interplay among large-scale ocean-atmosphere oscillations such as the El Niño-Southern Oscillation, the North Pacific Decadal Oscillation, the Arctic Oscillation/North Atlantic Oscillation, and the Asian and African monsoon systems. Lakes and, in particular, laminated lake sediments provide the opportunity to reconstruct these climate oscillations in selected sensitive regions around the globe. These climate data will also provide data about extreme climate events such as major droughts and floods that have had severe socio-economic consequences for past civilizations.
- To investigate the continental response to climate variability at centennial-to-millennial timescales such as the large amplitude Dansgaard-Oescher events of the last glacial period and lower amplitude Holocene and earlier interglacial variations.
- To understand potential shifts in interannual-to-decadal climate variability *during* the course of abrupt climate change, e.g. the start of the Bølling warm period (14,600 BP calendar years) the onset and end of the Younger Dryas (~12.7 to 11.5 ky BP calendar years), the Holocene "Little Ice Age“ (i.e., three periods of cooling between 1550 and 1850 AD), and glacial inceptions (e.g., 115 ky BP).
- To quantify how interglacial modes of climate variability at centennial-to-millennial timescales modulate climate variations at higher frequencies such as the North-Atlantic Oscillation and El Niño/Southern Oscillation during the Holocene, Eemian, and Marine Isotope Stage 11 (~410 ka).
- To understand the varying duration and amplitude of interglacials during the late Quaternary in the context of future change.

The analysis of laminated and high-sedimentation rate lake-sediment sequences is instrumental to expanding our understanding of rapid climate changes in low and high latitudes, as it provides unique opportunities (and in the low latitudes, in the absence of continental ice sheets, the only opportunity) to answer the questions above. In particular, the integration of terrestrial and marine archives, which have heretofore been considered largely in isolation, will improve greatly our mechanistic understanding of the Earth’s climate system. The cornerstones to such integrations are precise chronologies and their reliable synchronization. Ideally, chronologies should be absolute, as can be achieved by the counting of distinct varves. If an absolute time scale cannot be achieved, other methods such as radiocarbon (AMS^{14}C) dating, paleomagnetism, or tephrochronology assure a rather precise age control. New non-destructive analytical techniques such as automated geochemical scanning in combination with 'established' geochemical, isotopic, and micropaleontological proxies enable us to produce a large number of high-quality climate records in lake sequences. In the case of varved sediments, we are able to achieve annual to subseasonal resolution. Based on previous efforts and the now much improved knowledge of lake archives in combination with sharpened analytical tools, the next ten years of continental scientific drilling will provide the appropriate sediment sequences that will become 'icons' in climate research.

2 History of Lake Drilling within ICDP

The lake drilling component of ICDP activities was initiated in 1994 with discussions between the leadership of the nascent ICDP and PAGES (the Past Global Changes Project of the International Geosphere-Biosphere Program). As a result of these discussions, ICDP and PAGES jointly sponsored a workshop on Continental Drilling for Paleoclimate Records, held in Potsdam in the summer of 1995. The workshop had two important outcomes, one of which was a report of the same name (PAGES Report Series 96-4), which is still widely cited for the scientific justification and operational protocols for lake drilling. The second important outcome of the workshop was the formation of a Lake Drilling Task Force (LDTF), which operated until 2002 in the interests of promoting the drilling of sediments from extant lakes. The LDTF issued a community-wide solicitation in 1996 for potential lake drilling sites and received more than 60 suggestions, a list to which several more lakes have been added. The LDTF also set some initial priorities for lakes to be drilled for paleoclimate records.

Two major issues remained unresolved through the late 1990s. The first arose from a difference in focus between PAGES, which was primarily interested in paleoclimate records, and ICDP, which promoted research more traditionally addressed by drilling, such as tectonics, basin evolution, and meteorite impacts. Through several meetings and the proposal-review process, a standard eventually evolved: prime lake drilling sites were those that contained excellent paleoclimate records but whose cored sediments (or subjacent rock) also could be used to address other major scientific questions.

The other major problem was a lack of a practical, affordable system for drilling from the surface of large lakes. After several meetings and a formal feasibility study, a system that would meet virtually all needs was envisioned, but then deemed to be much too expensive. At this point, DOSECC (Drilling, Observation, and Sampling of the Earth's Continental Crust, Inc., a non-profit U.S. company that exists to facilitate continental scientific drilling) began discussions with a grass-roots group of scientists to examine the priorities and trade-offs involved. What eventually emerged was the design of the GLAD800 drilling system (Global Lake Drilling to 800 m), which addressed most of the community's priorities. Key capabilities included penetration (water plus sediment) of 800 m, a standard core diameter, a range of customized coring tools including a hydraulic piston corer for soft sediment, and the ability to operate (anchored) in 200 m of water. As originally designed, the system did not have the capability to drill in the deepest lakes or to operate in bad weather—these were the trade-offs made to keep it affordable.

Table 1. Successful ICDP co-sponsored lake drilling projects in the past 10 years

Name	Location, year	Lead PIs	No. of Sites	Sediment recovered
Great Salt Lake/Great Bear Lake	Utah, USA, 2000	Kaufman, Dean, Bright, Rosenbaum	5	500 m
Lake Titicaca	Bolivia/Peru, 2001	Baker, Fritz, Seltzer	3	625 m
Lake Bosumtwi	Ghana, 2004	Koeberl, Milkereit, Overpeck, Scholz	5	1833 m
Lake Malawi	Malawi, 2005	Johnson, Scholz, Cohen, King, Talbot, Odata, Dolozi, Kalindakafe, Tiercelin	2	623 m
Lake Qinghai	Central China, 2005	An, Colman, Haug, Molnar, Kawai	13 2	323 m * 1737 m
Lake Péten Itzá	Guatemala, 2006	Hodell, Brenner, Anselmetti	7	1327 m

*Upper total is for cores taken in the modern lake; lower total is for drilling just onshore into emergent lake sediments.

The capital costs of the GLAD800 system were funded by ICDP in 2000, and the system was built by DOSECC, which continues to operate it. As an initial test of the system, holes were drilled to more than 100 m in the Great Salt Lake and Bear Lake, near the DOSECC offices and workshops in Salt Lake City. The first major research project to use the GLAD800 system was at Lake Titicaca in 2001. Lake sediments and underlying impact breccias were drilled at Lake Bosumtwi (Ghana) in 2004, and the GLAD800 system was used to drill Lake Qinghai (China) in 2005 and Peten-Itza (Guatemala) in 2006. Also in 2005, ICDP supported a drilling operation in Lake Malawi (Africa) that used the GLAD800 coring tools, but used a larger drill rig mounted on a dynamically positioned barge. Other systems have evolved from the GLAD800 concept, including smaller systems (GLAD200) and systems that incorporate heave compensation (AHC800). ICDP has supported many planning workshops for lake drilling projects, and more well-justified research projects are in the wings, waiting only for adequate funding (Table 1, Fig. 2).

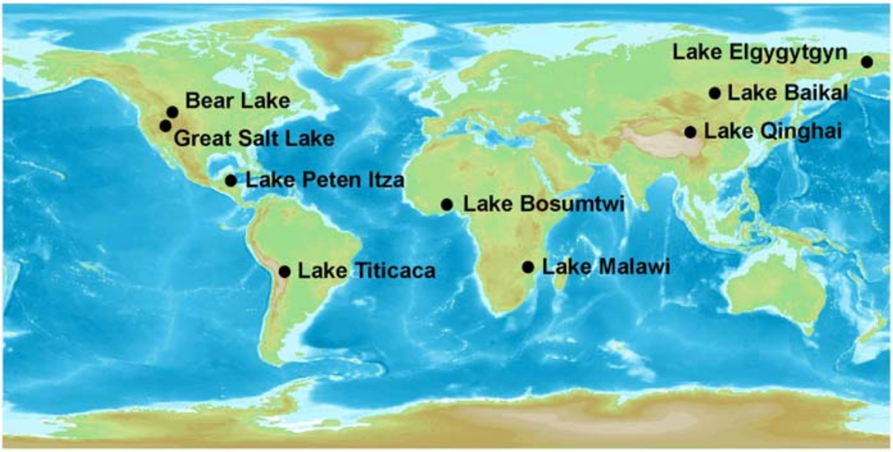

Fig. 2. World map with locations of ICDP drilling projects.

3 Successes in Lake Drilling

3.1 Proof-of-Concept Drilling in Great Salt Lake and Bear Lake

Initial development and testing of a modular lake-drilling system (GLAD800) took place during 1999-2000, culminating in the first tests and "proof-of-concept" drilling activities at Great Salt Lake (GSL) and Bear Lake (BL) (USA) in August/September 2000. During that work the modular drilling platform (*R/V Kerry Kelts*) and the GLAD800 drill rig (a modified wireline coring rig; Fig. 3) were deployed for the first time. Additionally the project tested a suite of new coring tools (the hydraulic piston corer, extended nose corer and the "alien" corer) developed by Marshall

Pardey (QD, Incorporated) and DOSECC that have become the backbone of ICDP's lake drilling efforts. Although the intent of the GSL/BL drilling was primarily to test the modular lake drilling system, the US NSF mandated that this testing be done in the context of scientifically important goals, a goal that was easily achieved in a region of long-standing paleoclimate interest (e.g., Gilbert 1890). A series of cores were taken from both deep basinal and marginal lake environments for both paleoclimatic and neotectonic studies. In all, approximately 500 m of core were recovered from five sites in the two lakes, with an average recovery of 93%. The longest of these cores (121 m in GSL and 120 m in BL) produced continuous paleoclimate records for the US Great Basin covering the last ~280 ky (MIS 8-present) and demonstrated a sequence of paleohydrological fluctuations on glacial/interglacial timescales comparable to the MIS2/1 (Lake Bonneville-modern GSL) transition (Schnurrenberger and Haskell 2001; Dean et al. 2002; Balch et al. 2005; Colman et al. 2005, 2006; Bright et al. 2006).

Fig. 3. GLAD800 rig and R/V Kerry Kelts during sea trial drilling at Bear Lake (photo by R. Conze).

3.2 The Lake Titicaca Drill Core Record of Tropical Climate Variability

Cores collected in Lake Titicaca in 2001 provide a continuous record of the timing of tropical glaciations prior to the last glacial maximum. The basin also contains the history of effective moisture in the tropical Andes and, perhaps, the adjacent Amazon basin, during the last half million years.

Such an archive is important for defining the nature of millennial to orbital scale climate variation in the tropics of South America and its phasing relative to the North Atlantic and monsoon regions of the Northern Hemisphere. Given the variety of controls on water balance on the Altiplano on a multiplicity of timescales, a long stratigraphic sequence can be used to assess the relative contributions of these controls, particularly the role of global temperature change and global-scale boundary conditions (Garreaud et al. 2003) relative to insolation control of the South American Summer Monsoon (or SASM; Zhuo and Lau 1998).

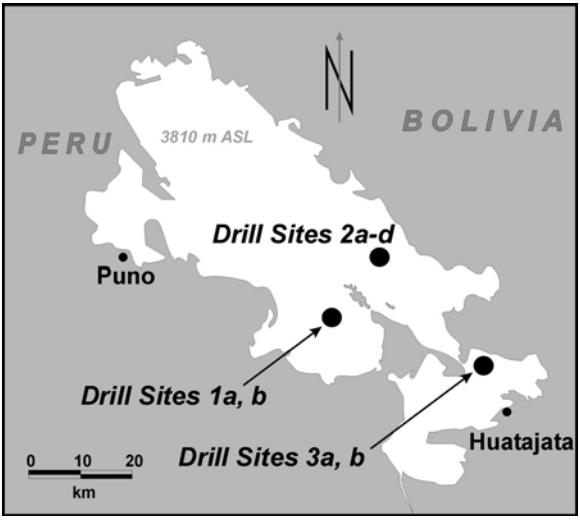

Fig. 4. Location of drill sites in Lake Titicaca completed in 2001. Lettering of sites 2a-d implies that four separate cores were taken (a,b,c,d) at one location.

In April/May 2001, 625 m of sediment was recovered at 3 locations in Lake Titicaca (Fig. 4). Sediments at each site consist of two major lithologic units: 1) gray mud that is massive, has high magnetic susceptibility, low organic carbon concentration, and no carbonate, and 2) a tan to green-gray mud that is laminated or thinly bedded and contains carbonate, high organic carbon concentrations, and low magnetic susceptibility values (Fig. 5). Based on earlier work in the basin (Baker et al. 2001a; Seltzer et al. 2002), the massive high-susceptibility units were determined to be predominantly of glacial-fluvial origin, with a high detrital content derived from glacial activity in the surrounding cordillera. The absence of carbonate and the dominance of freshwater planktonic diatoms suggest a fresh overflowing lake. The laminated units, which contain carbonate and have low magnetic susceptibility values, are primarily of lacustrine origin and reflect times when detrital input from the surrounding watershed was low and when lake level was below the outlet threshold, driving carbonate precipitation from the water column. Thus, the laminated sediments represent intervals of reduced precipitation and reduced glacial extent.

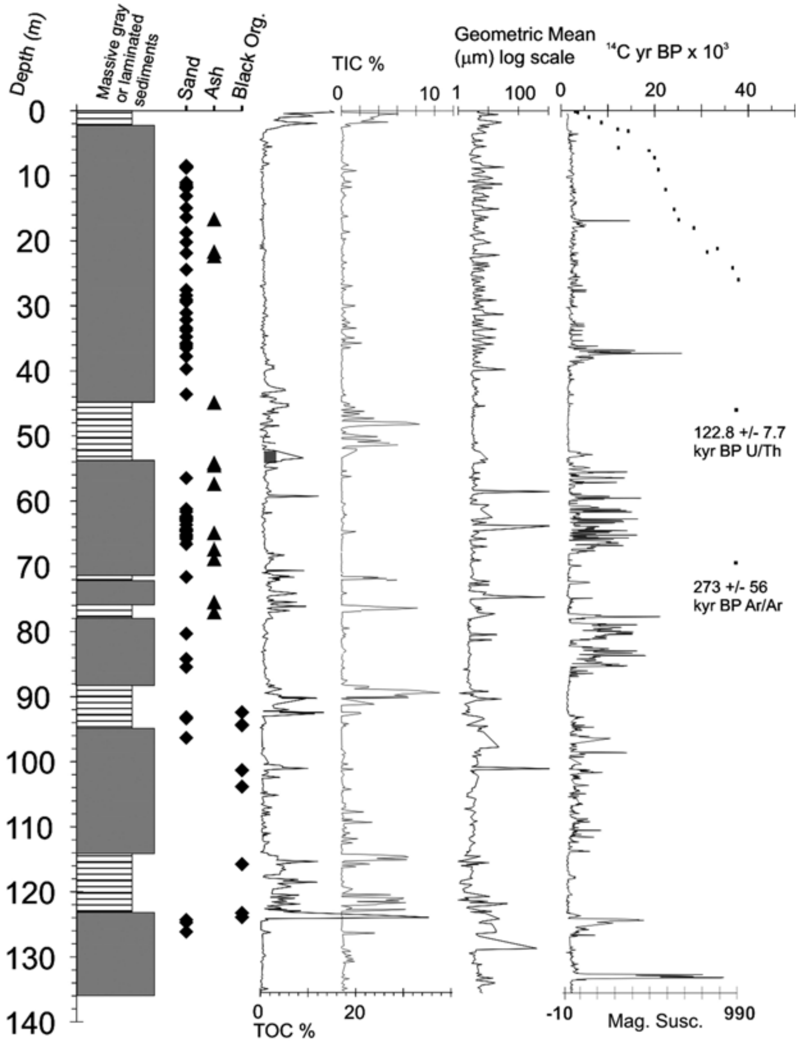

Fig. 5. Physical and geochemical stratigraphy from Lake Titicaca. Left column outlines the overall sedimentology. Additional columns from left to right include total organic carbon (TOC%), total inorganic carbon (TIC%), geometric mean log scale, and, finally, magnetic susceptibility. Numerical dating control is outlined in the rightmost column.

Analyses have focused on site LT01-2B (235 m water depth), which is the longest of the sedimentary sequences drilled (total sediment length = 136 meters below lake floor, mblf). The drill core from this location consists of four major massive units with high magnetic susceptibility that alternate with low-susceptibility units. This stratigraphy suggests that the core spans four major periods of glaciation and subsequent interstadials of the fifth glaciation. The chronology of each core site is constrained by AMS ^{14}C analyses on bulk organic matter and, in site 2B, several uranium-series ages on thin aragonite laminae in the upper part of the penultimate interstadial unit (~45 m blf). ^{40}Ar-^{39}Ar dating of interbedded ashes in the drill cores produced unreliable ages, apparently because the samples contain high detrital biotite not associated with the direct ash fall. Extrapolation of the calibrated radiocarbon chronology to the base of the uppermost high-magnetic susceptibility unit can be used to define the onset of extensive glaciation in the surrounding cordillera. Based on the range of dates from each of the three drill sites, the onset of the most recent period of glaciation began between 55,000 and 70,000 years ago, (50 – 64 ^{14}C years BP), thus during the equivalent of Marine Isotope Stage 4 (MIS4).

In the LT01-2B core sequence, only three meters of mud separate the onset of the most recent glacial stage (~65,000 yr BP at 42 mblf) and the termination of the penultimate (pre-Holocene) interstadial period (~45 mblf), which (based on U-series ages on aragonite layers) dates from about 120,000 years ago, during marine isotope sub-stage 5e (MIS5e). If the ages are correct, either sediment accumulation in this transitional interval was very slow, because of the low inputs of material from within the watershed, or alternatively that there is a depositional hiatus in the record, which encompasses much of MIS5. The former scenario has been assumed in modeling sediment accumulation rates; however, both scenarios would produce similar low rates.

To create an age model for sediments prior to 120,000 cal yr BP, peaks in the LT01-2B calcium carbonate record representing times of lower lake level and reduced regional precipitation were tuned to peaks (enriched values) in the Vostok CO_2 record (Petit et al. 1999). This parsimonious approach yields a roughly linear sediment accumulation rate through time, averaged over the entire core sequence. Application of this age model to the drill core sequence suggests that the entire 135 m core spans approximately the last 400,000 years. Based on this model, the major Lake Titicaca lowstands (highstands) are approximately synchronous with global warm (cold) periods evident in the Vostok sequence, suggesting that Lake Titicaca hydrologic balance (and possibly that of the Amazon basin) responds to global-scale temperature changes (Baker et al. 2001a). This impact on water balance is likely a result of a direct temperature control on evaporation rate. In addition, tropical Pacific or Atlantic SST patterns might have affected precipitation amounts in the Amazon and tropical Andes (Baker et al. 2001a; Nobre and Shukla 1996). Precessional controls on summer insolation and the SASM have also been shown to be an important forcing of the hydrologic balance of the Altiplano (Baker et al. 2001; Wang et al. 2004).

A comparison of the magnetic susceptibility record of glacial expansion and contraction, with the δD or pCO_2 record from Vostok, suggests that glacial stages in the tropical Andes were approximately synchronous with high-latitude glacial stages and globally cold climate. Although this conclusion is not surprising for the LGM, the timing relative to previous glacial stages was previously unknown. The timing of glacial expansion inferred from the Titicaca drill cores is also supported by recent studies of ^{10}Be exposure ages and estimated rates of boulder erosion and surface uplift in the Junin basin of Peru (Smith 2005).

3.3 The Lake Bosumtwi Project

Lake Bosumtwi occupies a 1.07 Ma impact crater located in Ghana, West Africa centered at 06°32'N and 01°25'W (Fig. 2). Because of its great age and location with respect to the North African monsoon, Lake Bosumtwi is ideally situated to provide a long record of tropical climate change. As the largest young impact structure on Earth, the Bosumtwi crater can also provide important new insight on impact events. To take full advantage of the geologic information contained in the Bosumtwi crater, a combined sediment- and rock-drilling program was undertaken in summer 2004. DOSECC Inc., using the GLAD800 was contracted to recover both sediment and rock cores. The success of the drilling effort was the result of the hard work of a dedicated group of DOSECC drillers, the Kilindi boat captain and a group of international scientists.

In July and August 2004, the sediment drilling subprogram was completed and serves as an example for how lake drilling can provide much needed insights into the workings of Earth’s climate system. Recent studies have suggested an important role for the tropical ocean and atmosphere in producing globally distributed climatic change including drought (Nicholson 2000; Visser et al. 2003; Hoerling and Kumar 2003). Additional studies have shown a temporal correlation between tropical and high-latitude climatic change, particularly North Atlantic thermohaline circulation, although the underlying causal mechanism is not completely understood (Alley et al. 2003; Broecker 2003). In order to gain greater insight into the role of the tropics in triggering, intensifying, and propagating climate changes, as well as in responding to global and high-latitude changes, additional high-resolution paleoclimate records from the tropics are needed. Recovery of long sediment records from Lake Bosumtwi offer the potential to examine tropical climate linkages over a variety of time-scales.

The GLAD800 lake drilling system was used to drill 13 holes at five sites in Lake Bosumtwi (Fig. 6; Koeberl et al. 2006). These drill sites were placed along a depth transect in order to facilitate the reconstruction of lake level history. Total sediment recovery was 1.8 km in 706 core sections. The complete 1 Ma lacustrine sediment fill was recovered ending in impact-glass-bearing, accretionary lapilli fallout representing the initial days of sedimentation. Much of the overlying 294 m of mud was found to be laminated, thus these sediment cores will provide a unique 1 million year record of tropical climate change in continental Africa at extremely high resolution. These sediments preserve a record of lake level variability that will extend further back in time existing and widely-cited Bosumtwi lake-level histories, obtained from high-stand terraces and short piston cores. Study of the abundant macrofossils within the cores can be coupled with microfossil, biomarker and geochemical measures to provide a robust record of terrestrial ecosystem change.

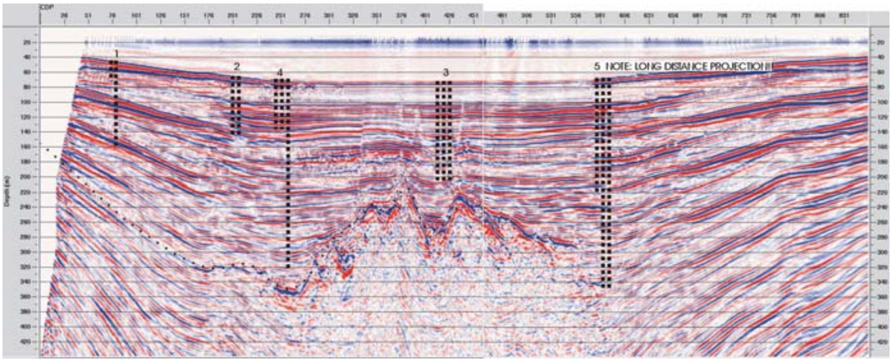

Fig. 6. Locations and depth of core recovery at the 5 sediment drilling sites from Lake Bosumtwi, summer 2004, plotted on the seismic-reflection profile (from C. Scholz). Lake floor and impact-brecciated bedrock of the central uplift are clearly revealed.

3.4 Lake Malawi Drilling in Africa

The Lake Malawi Drilling Project (LMDP) represents the first effort to drill the East African rift valley lakes, a long recognized region of interest for obtaining long tropical paleoclimate records (Johnson et al. 1990; Cohen et al.

2000). The LMDP was conducted in Feb-Mar 2005, with a primary goal of documenting the timing of major climate cycles in East Africa over much of the Pleistocene and their potential relationship to orbital forcing and glacial cycles. It was the most logistically challenging lake drilling effort to date, using a much larger rig and platform than prior efforts (Seacore's CS-100, Fig. 7). The LMDP was also the first lake drilling effort to employ dynamic positioning (DP) successfully; DP was required instead of anchoring because of the great water depths of the coring targets (Fig. 8). The LMDP recovered 623 m of core (92% core recovery) from two sites. A deep-water site (~600 m water depth) in the lake's central basin, cored to 381 mblf (meters below lake floor, double-cored to 80 m) is estimated to contain a high-resolution record of climate change for East Africa covering the last 1-1.5 Ma. A second, shallower water target (350 m water depth) was chosen in the north basin because it had previously yielded a very high-resolution 9m core record covering the past 25ky (Johnson et al. 2002) and seismic reflection data indicated the same partially laminated facies persisted to ~40 mblf. The entire facies package was drilled (triple-cored), which should yield a similarly continuous record of detailed climate change over the past ~100 ka.

Fig. 7. Lake Malawi drilling project barge *Viphya* and SEACORE CS-100 drill rig on station in northern Lake Malawi with rift valley escarpment in the background. Three of the four thrust-master dynamic positioning engines (blue) are visible at the bow and stern of the barge (photo by J. Agnitch).

3.5 Lake Qinghai Drilling in China

Lake Qinghai in central China was selected as a world-class target for lake drilling due it its strategic location northeast of the Tibetian Plateau but west of the world's most expansive loess sequences recording the timing and pace of glacial/interglacial change over the past 3.5 million years. Being heavily influenced by regional tectonics, the region surrounding the lake is today affected by three major atmospheric circulation systems that interface at the transition between the strong East Asian Monsoon and the dry inland regions dominated by the westerlies (Fig. 9).

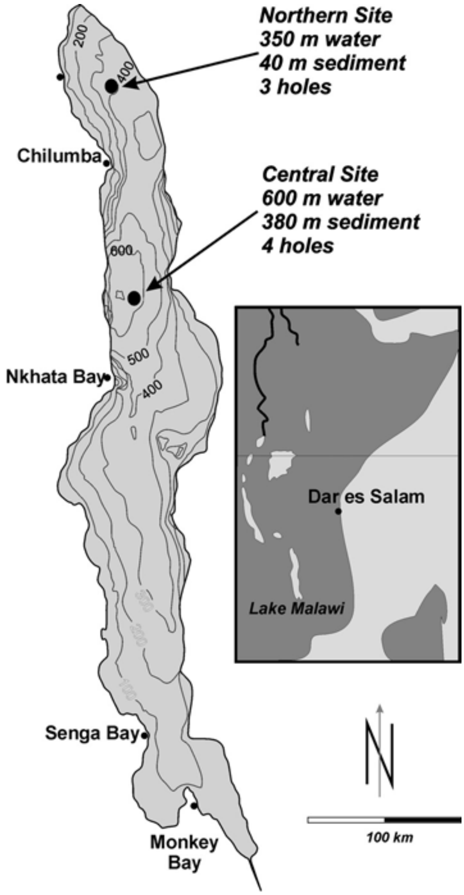

Fig. 8. Bathymetric map of Lake Malawi with the 2005 coring sites shown. The mean depth of the lake is about 282 m.

Drilling at Lake Qinghai was carried out in the summer and fall of 2005 in order to obtain an improved understanding of the late Cenozoic environmental history of the Lake Qinghai region and the development of the East Asian Monsoon climate, understand the Lake Cenozoic tectonic evolution of the Lake Qinghai basin and the growth of the northeastern margin of the Tibetan Plateau and its effects on regional climate, and finally correlate Lake Qinghai environmental records with other regional and global paleoclimatic records to obtain a better understanding of the connection between regional climate change, the development of the East Asian Monsoon system, prevailing westerlies and ultimately, the evolution of global climate (An et al. 2006).

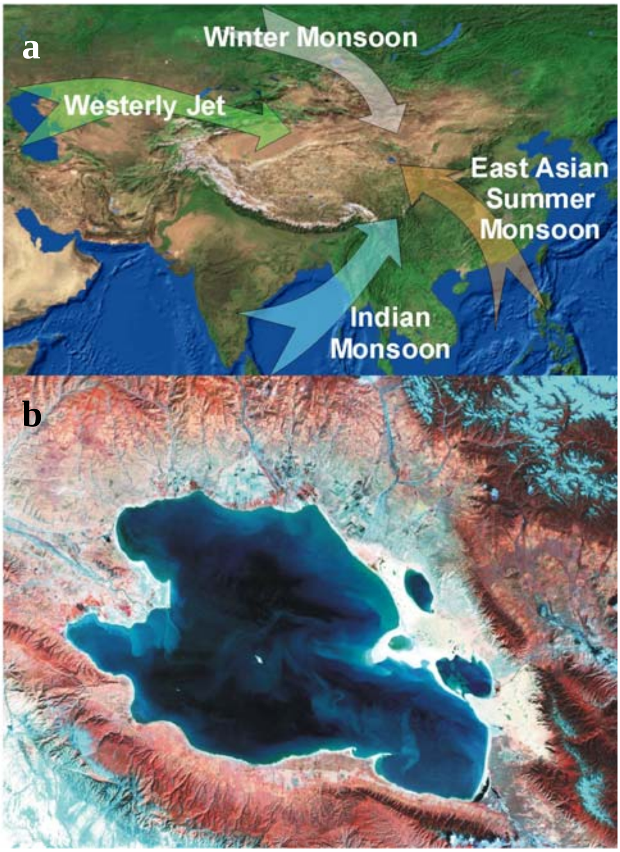

Fig. 9. a. Map showing how the climate of central China is influenced by the East Asian and Indian summer monsoons, Siberian winter monsoon and the westerlies. In summer warm, moist summer monsoons dominate over southern and eastern China reaching Lake Qinghai. In winter, the Siberian monsoon dominated, blowing cold dry air over much of China; the westerlies are split by the Tibetan Plateau. **b.** Satellite image of Lake Qinghai.

Despite the challenges of an infectious bird flu outbreak and poor weather conditions, drilling using the GLAD-800 coring system on the modular ICDP super barge successfully recovered 323 m of sediment from

13 sites across the basin with excellent recovery of the upper 30-50 m of the sediment sequence consisting of mainly gray clay and silty clay. Penetration to below 30-50 m proved to be difficult due to the presence of a laterally continuous sandy section compounded by rough waves and wind. Recovery of a proposed 700 m lacustrine sediment sequence from the deep basin was postponed to the future, but 2 sediment cores reaching depths of 1109 m and 628.5 m were taken with 90% recovery from the basin at the edge of the lake by the Qinghai Geological Survey.

At least 60 scientists from China, Japan, Europe and North America have expressed interest in participating in a range of studies of the recovered core materials. The first results from this project are forthcoming.

3.6 Lake Peten Itza Drilling in Guatemala

Lake Peten Itza, the deepest lake in Central America, is a tectonic basin that persisted even during dry portions of the last few glacial cycles. For this reason the lake offers one of the few sedimentary archives available for decadal to millennial resolution studies of climate variability during the late Pleistocene and Holocene in this tropical region. The proximity of the lake to the outstanding records from the Cariaco Basin (Fig. 1, and Fig. 10) made this a key drilling target for testing the low latitude land response to ocean/atmospheric climate change operating at global scales.

Drilling of Lake Peten Itza took place in the early half of 2006 during the dry season using the GLAD800 hydraulic piston coring system (Anselmetti et al. 2006). With an average recovery of about 93%, a total of 1327 m of sediment was recovered at seven sites with double and triple offset coring at some locations to ensure recovery of a continuous depositional sequence. Preliminary interpretations based on sediment density, p-wave velocity, magnetic susceptibility and smear slides suggests that the basin records an abrupt transition from Late Glacial dense gypsum sand interbedded with silty clay to Holocene gray clay thought represent a shift from a dry glacial climate to more humid early Holocene conditions. Studies are ongoing to determine the age of the deepest samples recovered. Scientists from a number of nations, including the USA, Switzerland, Germany, Mexico, Guatemala, Argentina, and France will be involved in the interpretation of the collected core materials.

4 Outstanding Scientific Possibilities for Future Drilling

The geographical density of available continental paleoclimate records spanning the Holocene has been used to reconstruct spatial patterns of past climate changes, providing considerable insight into post-glacial climate dynamics and its forcing mechanisms (e.g., Mayewski et al. 2004; Partridge et al. 2004; Verschuren 2004; Rohling and Pälike 2005). A growing number of these continental records are lake records, obtained for the most part by lake coring to fairly shallow depths. An important question to be answered – given the cost – is this: *what can we learn from continental lake drilling that we can't learn from inexpensive coring?* The answer is clear.

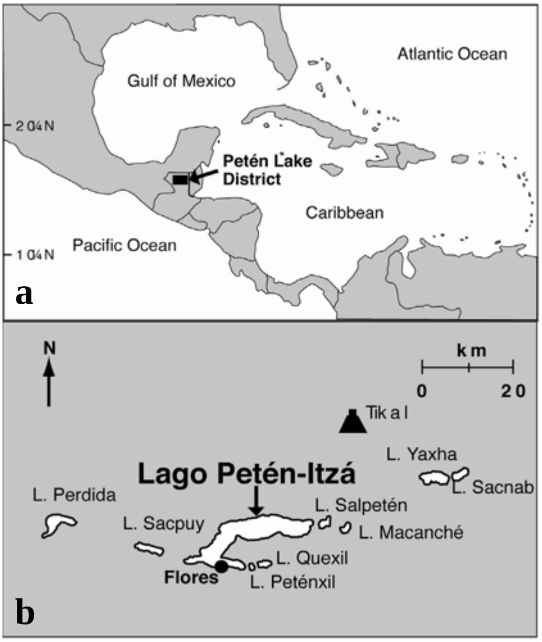

Fig. 10. a. Map of the circum-Caribbean region showing location of the Central Peten Lake District in northern Guatemala and the Cariaco Basin off northern Venezuela. **b.** Details of the Central Peten Lake District showing Lake Peten-Itza (after Anselmetti et al. 2006).

The period since Termination I (~ 12 ka) contains too few millennium-scale climate events to produce a general understanding of the origin, propagation and phasing of climate variability. Also, post-glacial climate records cannot speak to the continental history of glacial-interglacial and orbital-scale climate changes and their exact linkages to the oceans, continental ice sheets, greenhouse gases, and orbitally-driven insolation variations. For this purpose a global network of long high-quality climate records is required. These records will more completely document the frequency, duration, amplitude, and rates of change of orbital- to multi-centennial scale climate fluctuations, the interactions among millennial and orbital-scale climate dynamics, and mechanistic similarities of climate change on different time-scales. Given that the continents are synoptic recorders of climate mechanisms, only with such a spatial network of longer records can the science community properly evaluate the geographical patterns and teleconnections of individual events across the globe, which is key to understanding the climatic processes involved. Spatial as well as temporal resolution in reconstructing past climate changes is therefore essential to understanding past and future climate dynamics and its effects on terrestrial environments. General circulation models have made use of marine and ice-core-derived paleoclimate data to make specific and often diagnostic predictions about the spatial patterns associated with mechanisms triggering and amplifying past climate changes. Examples include terrestrial rainfall patterns resulting from the role of the El Niño Southern Oscillation system in amplifying or triggering millennial-scale climate changes (Cane and Clement 1999), and the likely influence that subtropical jets and tropical moisture export have on high-latitude ice sheet growth (Yin and Battisti 2000). Unlike ice-core and most marine records, continental climate archives record regional hydrologic and climatic responses to atmospheric change, providing a record that is key to resolving climate dynamics at fine spatial scales relevant to both climate modeling and societal impacts of climate change. This point is key. Thus, a well-chosen network of long continental climate records could play an instrumental role in testing climate models predictions and ocean-atmosphere connections.

5 Potential Targets

Long continental paleoclimate records can be gleaned not only from lake deposits, but also from loess, paleosols, and speleothems. Given the demanding criteria of record continuity and resolution, the drilling of lake deposits will be instrumental if not essential in filling the spatial gaps left by marine and ice core records. Lakes are widely distributed on the continents and integrate a record of climatic change at scales of tens to thousands of km^2, thus providing the spatial resolution, density, and replication necessary to identify geographical patterns of past climate change.

Long high-resolution records making up this climate dynamics network should cover at least one, and preferably several, complete glacial-interglacial cycles with stratigraphic continuity, time resolution and age control comparable to that of the ice-core records from Greenland and Antarctica. The costs of ICDP drilling necessarily imply that the global network of long records will be less extensive and less dense than is achievable by traditional coring techniques for Holocene studies. However, extensive lake exploration over the past decade suggests that the number of lakes worldwide possessing a demonstrated or probable high-resolution, continuous climate-proxy archive with a minimum age exceeding $150x10^3$ years may be rather limited. In many lakes a complete glacial-interglacial cycle is within reach of the GLAD200 system, which can be deployed at modest cost. Recovering longer records to test the full range of glacial-interglacial and shorter-term climate variability across multiple glacial cycles will require slightly larger investments, probably at a somewhat more limited suite of sites. Thus, given conditional and careful site selection with needs of geographical and temporal resolution in mind, it may be feasible for ICDP to pursue completion of this climate-dynamics network over the next decade, with drilling projects in strategic locations across the tropical, sub-tropical, and temperate continental regions.

Lake records from some strategic locations, including the tropics and polar regions, will be more instructive than others in revealing the past dynamics of certain important weather systems. For example, a suite of lake sites spanning the African tropics, subtropics, and European mid-latitudes should be capable to test for changes in the position of the air masses and subtropical and mid-latitude jet streams responsible for heat transport to the North Atlantic. A similar transect of lake records positioned strategically along the Pacific rim should be capable of testing teleconnections between ENSO circulation, long term changes in the Pacific North American Oscillation and changes in the Siberian High. Given sufficient longitudinal coverage, such a network may also resolve past changes in Walker circulation through analysis of the relative influence of the Indian and Atlantic Ocean monsoons on intertropical African rainfall. This information should begin to disentangle the relative amplifying effects of latitudinal shifts in zonal circulation, the ENSO system, and tropical convection on global climate variability at millennial to orbital time-scales. Drilling in NE Russia from the first Arctic site is planned at Lake El'gygytgyn crater (Fig. 2) in spring 2008 to capture a record of climate change back to 3.6 million years. Other projects currently under consideration and at the workshop phase include studies of Lake Van, Turkey, and Lake Potrok Aike, southern Argentina.

6 Other Scientific Returns

6.1 African Lakes and Human Evolution

Paleoclimate has long played a central role in hypotheses about human evolution. Since the early part of the 20th Century, when Late Neogene aridification was linked to a shift from arboreal to terrestrial human habitats, paleoanthropologists have made increasingly sophisticated use of available paleoclimate data in their attempts to understand our origins. Over the last 20 years hypothetical links between environmental change and human evolution have become more explicit and refined. Examples include the pulsed speciation and turnover hypothesis (Vrba 1988; 1995), that postulates that hominid evolution occurred during distinct pulses in response to Plio-Pleistocene transitions in mean paleoenvironmental conditions, and the climate variability hypothesis (Potts 1996), which suggests that hominids evolved in response to increased spatial and temporal heterogeneity in African paleoenvironments.

These hypotheses concerning the mechanisms of hominid evolution generate potentially testable hypotheses linking climate and evolutionary change, and require data from both paleoclimatology and paleobiology to be tested. Existing outcrop and ocean drilling records have previously been used to support various ideas about the hominid evolution/climate linkage, and especially to explain bursts of evolutionary change at ~2.8, 1.7, and 1.0 Ma (e.g., DeMenocal 2004). However, these records are inadequate to fully test current hypotheses, either because they are incomplete or of low resolution (most outcrop records) or because they homogenize paleoenvironmental records on spatial scales that are too large to be appropriate for testing the hypotheses (as with marine drilling records). Drilling African lakes can fill this gap by providing continuous, long sedimentary archives that record paleoenvironmental changes occurring at the regional spatial scales required to test the competing theories of hominid evolution.

6.2 Subglacial Environments (SALE)

More than 98% of Antarctica and most of Greenland is covered by thick ice masses making access to the subglacial environment difficult. However, this environment contains paleoclimatic and paleo-ice sheet records of global importance. They are key to a more complete understanding of major changes in climate history over the last 60 Ma like the inception and evolution of not only the East and West Antarctic and Greenland ice sheets but also major steps like the change from ~40 to 100 ky glacial cycles. Access to the subglacial bed is also of great importance for the assessment of future changes. Subglacial conditions are playing a key role in the dynamics of ice sheets and thus an improved knowledge is essential for understanding ice sheet dynamics and prediction of future sea-level changes.

Subglacial bed properties and properties of underlying geologic units not only play a key role in the ice-bed interaction, they also contain important climate records or records of ice sheet evolution and subglacial processes. For example, soft marine sedimentary basin fill in West Antarctica provides an easy erodable subglacial bed, which together with the availability of subglacial water is key to the formation and evolution of its fast flowing ice streams (Anandakrishnan et al. 1998; Bell et al. 1998; Tulaczyk et al. 1998; Tulaczyk et al. 2000). The sedimentary basin fill also contains paleoclimatic records covering for example the period from the inception of the East Antarctic ice sheet in the early Paleocene to the build-up of the West Antarctic Ice Sheet (e.g., DSDP, DVDP, Cape Roberts Project, and ANDRILL). In addition the deformational till layer at the ice-bed interface also contains paleo-environmental records of fluctuations in ice sheet extent (e.g., Anderson and Shipp 2001; Domack et al. 1999; Scherer et al. 1998) or the temporal evolution of subglacial conditions (e.g., Vogel et al. 2005).

Subglacial water plays not only a key role in the dynamics of ice sheets it also is essential for the existence of life in this extreme environment. Subglacial lake environments, forming in subglacial basins, provide a unique habitat for life. Subglacial lake basins also serve as sediment traps and likely contain important and unique paleo-climate and paleo-environmental records. These records have the potential of elucidating the inception and build up of these large ice sheets as well as their evolution. Specific targets that could be considered in the future in Antarctica and Greenland are:

- Former marine or continental sedimentary basins,
- Subglacial lake environments,
- Subglacial volcanism,
- Physical properties of the crust,
- Ice streams and ice stream tributaries,
- Grounding zones and sub ice shelf environment.

6.3 Paleoseismicity and Rates of Tectonic Process

Lake records in strategic geographic locations offer the science community opportunities to understand both past and ongoing rates of tectonic activity. For example, the location of the Dead Sea on a major transform fault makes it an ideal target for studying paleo-earthquakes. The world's longest and highest-resolution record of seismites (earthquake induced sedimentary structures) was recovered from an exposed section at Lisan (Marco et al. 1996), and from exposures and several boreholes drilled into the Holocene sedimentary section along the retreating shores of the Dead Sea (Ken-Tor et al. 2003; Migowski et al. 2004). Radiocarbon dating and annual laminae counting yield excellent agreement between the disturbed sedimentary structures and the historical earthquake record. A total of 78 Holocene events suggest varying recurrence intervals between a few years to more than 625 years, with maximum seismicity during the past 6-8 centuries. Moreover, it seems clear that Dead Sea Thrust (DST) seismicity correlates with movements along the North Anatolian Fault, as opposed to the intervening East Anatolian Fault. Recent work suggests that plate-scale elastic coupling may underlie escape tectonics typical of continental collision.

These studies suggest that drilling into appropriate lacustrine archives located along major faults could provide high-resolution information on the spatial and temporal distribution of earthquakes. This is critically important for human societies inhabiting tectonically active regions, e.g., in particular in the case of the North Anatolian fault where major human disasters have occurred in recent years.

The Quaternary lakes that once occupied the tectonic depressions along the Dead Sea rift valley have been characterized based upon changes in salinity and their limnological configuration and geography. While Lake Hula and the Sea of Galilee were fresh water bodies that supported life, Lake Lisan and the Holocene Dead Sea were terminal hypersaline water bodies that supported only limited forms of life (Hazan et al. 2005). These lakes co-existed, opening the possibility for interdisciplinary investigations into sedimentation and bio-geochemical processes in distinct environments under similar climatic and hydrological forcings at various time scales. Thus, retrieving high-resolution long-term records from water bodies such as these would be of great scientific interest with societal relevance. Similar complementary tectonic and Quaternary studies should be sought where chained lake systems of a similar nature exist.

6.4 Extreme Event Stratigraphy and Hazards

An issue of increasingly critical concern with strong potential for crossover between the geosciences and risk assessment/management communities centers on the frequency and magnitude of a variety of earth and climate system processes (e.g., extreme storms, floods, seismic events). Modeling provides one important means of testing these systems, but long records suitable for validation of these models are particularly rare. Sedimentary records are ideally suited to investigate the long term dynamics of extreme "events", and in many instances, have recorded the event as a distinctive sedimentary deposit that can be placed in a long term chronological context (Lamoureux 2000; Noren et al. 2002). Event stratigraphy can be readily incorporated into standard sediment logging and sampling protocols. Evolving high-resolution sediment imaging and scanning analysis provide rapid, non-destructive means to obtain event information, while statistical frequency analysis (Katz et al. 2002) can be used to quantify event frequency-magnitude characteristics. In cases where varved sediments are present, the potential exists to develop information and probabilistic models for annual maximum events (e.g., floods) that can be directly compared with model outputs.

Relatively short records are widely available from many regions of the world providing long term indications of environmental changes during the Holocene. However, relatively few continental settings can provide sedimentary archives that are suitable for extreme event stratigraphies extending over longer periods (10^4-10^6 years). A key advantage of the deep time sedimentary system is the opportunity to investigate the frequency-magnitude characteristics of extreme events with a broader range of environmental forcings, including higher global temperatures, high levels of greenhouse gas concentrations, and changes in the configuration of major climate systems (e.g., monsoonal systems), ice cover, and ocean circulation. These deep time environmental settings, viewed through long sedimentary records, provide a key opportunity to understand potential risks in the future climate system. They provide a particularly unique opportunity to evaluate future extreme event properties in projected anthropogenic greenhouse climate scenarios.

6.5 Paleo-Hydrology and Drought Stratigraphy

Climate archives that develop annual growth bands or laminae have been prime targets for the investigation of decadal and centennial paleoenvironmental cycles. These are mainly trees, corals, ice cores, rare marine cores and laminated lake sediments. However, lakes located in particularly sensitive regions can provide contemporaneous information across arid, semi-arid and moister climate zones. Because the late Holocene alone lacks systemic changes of the magnitude and direction the Earth may face in the coming centuries, climatic changes and hydrologic feedbacks are best assessed in the context of earlier intervals of climatic extremes and transitions (Bartov et al. 2003). This is especially important where major, perhaps rapid shifts toward drought would have serious consequences for modern societies requiring international collaborations for the mobilization of water supplies.

Archeological examples of drought stress on societies provide some context for this on regional scales. For instance, several investigators have hypothesized that rapid (catastrophic) climate shifts had an impact on human cultural history in the Near East and drove societies to total collapse (cf. Neev and Emery 1995). The drilling of lakes along the African-Syrian Rift (e.g., Dead Sea, Lake Van, and the East African lakes) could provide patterns of climate changes in millennial to decadal time resolution across several climatic zones, provided that high-resolution calendar chronologies can be established in all locations. In particular, the science community is interested in terminal and amplifier lakes that behave as a hydrological gauge for a large drainage area.

7 Best Practices and Principles

Growing interest in complex lake drilling to meet scientific goals has resulted in some growing pains for nearly everyone involved – from the level of principle investigator, to logistics providers, drillers, funding agencies and their program managers. Without doubt, the road map for successful lake drilling, one that starts out with a good idea and ends with high-quality core material stored safely at 4°C in the laboratory, can be bumpy and full of obstacles. As a consequence of experiences in recent years, DOSECC, Inc., led the way by convening a US National Science Foundation workshop in 2003 of scientists and operators to develop manuals characterizing the essential stages and steps required for developing a scientific project (Nielson and Cohen 2003); a second manual (Nielson 2003) provides an introduction to drilling operations. Both of these manuals have been adopted, in principle, by the ICDP as essential guides for the scientific community. Both can be downloaded from the web at www.dosecc.org. What is critically important about these documents is that they outline very clearly the scope of planning (e.g., Fig. 11) that is absolutely necessary for any lake drilling project – large or small – to be successful.

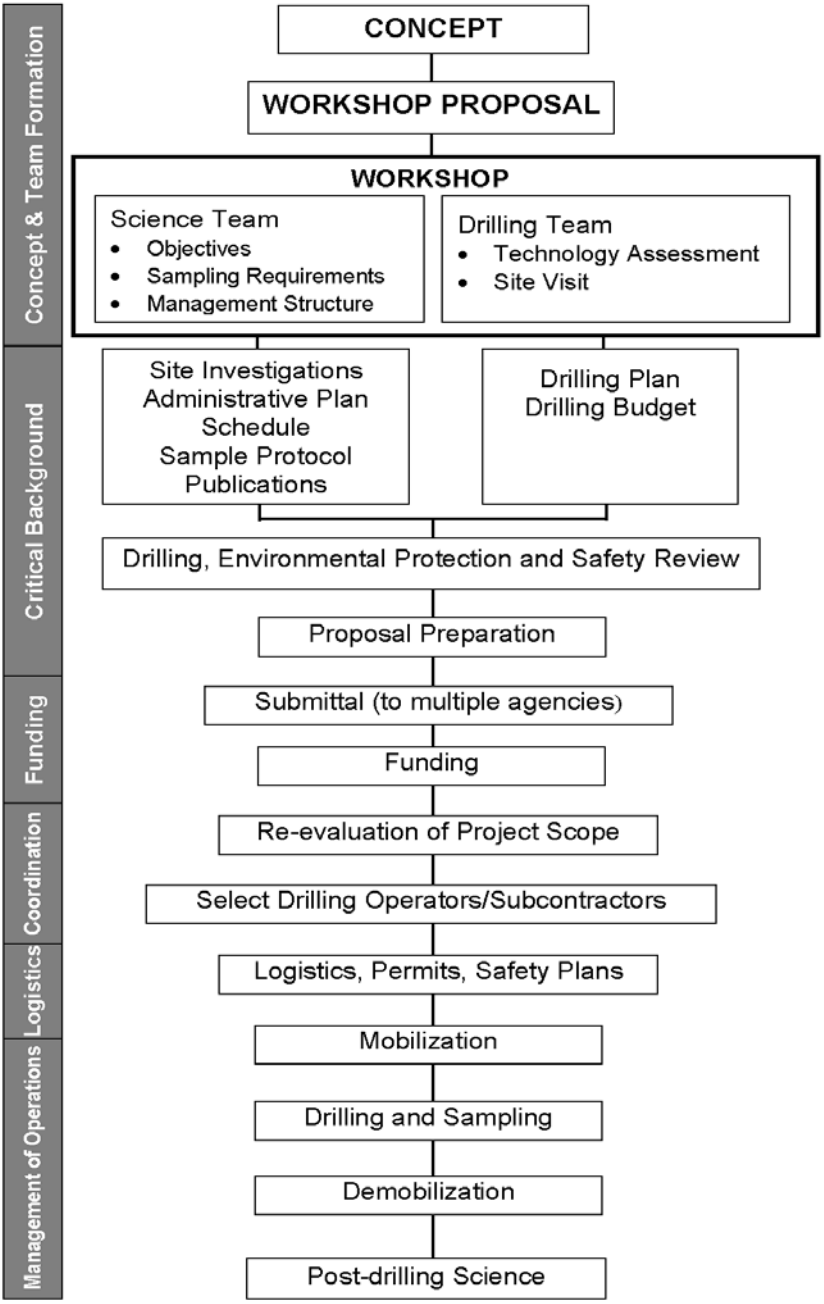

Fig. 11. Scientific Drilling Flow Chart (after Cohen and Nielson 2003).

8 Technology and Other Needs

8.1 Existing Drilling Tools

Historically, scientists interested in sampling modern lakes have used equipment that was inexpensive and simple to use but limited in the length of core that could be collected (Colman 1995). At the other end of the spectrum, the off shore petroleum and geotechnical industries have long operated large rigs with capabilities to drill deep holes in deep water. What was needed was a system to collect relatively long cores in lakes, so in response to this scientific requirement, DOSECC undertook the design of the GLAD800 (Global Lake Drilling to 800 m) that was built under a joint venture between DOSECC and the ICDP. The GLAD800 (Fig. 3) has formed the basis for two additional systems, the GLAD200 (Fig. 12) and the heave-compensated AHC800 that utilize the same down-hole tools and drill string. There are plans to construct a new rig specifically for drilling on frozen lakes, and the GLAD800 coring tools are now used for the collection of samples from the larger geotechnical rigs such as was done on Lake Malawi using Seacore's CS-100 (Fig. 7). Therefore, the development of the GLAD800, sponsored by ICDP, has filled a critical gap in coring capability, and the scientific community has access to a full spectrum of drilling technology.

Fig. 12. The GLAD200 drilling facility on an Icelandic lake. The drill rig has a capacity of 200 m drill length, the barge is 10 by 5 m (photo by D. Nielson).

The GLAD800 (Fig. 3) includes a barge, drill rig, drill rods and riser pipe, down-hole tools, parts inventory and shop. The system can be transported nearly anywhere in the world in 20-foot shipping containers.

A variety of different drilling tools are required to collect the different types of sediment encountered in modern lakes (Fig. 13). The GLAD800 includes six standard tools, listed below in order of increasing stiffness of sediment. These tools fit within an outer assembly that drills a hole 139.7 mm (5.5 inches) in diameter.

- Shelby “push” tube.
- Hydraulic piston core (HPC).
- Extended shoe, non-rotating.
- Extended core bit, rotating (The Alien).
- Diamond core bit (mining).
- Non-sampling assembly.

8.2 Needed Drilling Tools and Changes

Lake drilling has experienced growing pains in the first successful years. Several important topics were either addressed or identified during the successful Lake Bosumtwi sediment drilling project, for example. Hence it is important that future lake drilling projects carefully consider these topics to ensure achieving their scientific drilling objectives.

1. Organization: In order to obtain the maximum geologic information contained in the Bosumtwi crater and achieve an economy of scale, a combined sediment- and rock-drilling program was undertaken. In order to have two diverse drilling programs within one project, a reasonable, guiding operations manager is required, and the Bosumtwi project was fortunate to have Dr. Uli Harms, GFZ-ICDP fill that role.
2. Magnetic orientation of sediment cores: Magnetically oriented cores are needed to construct downcore declination profiles and thus to more completely characterize the geomagnetic field and construct robust paleomagnetic age models. At Lake Bosumtwi a new magnetic-bearing orientation device was used on the HPC corer for the first time in an attempt to recover magnetic declination records from the drill cores. Preliminary results suggest that useful magnetic orientation information was recovered some of the time. A limitation of the system was that it could only be fitted to the HPC corer and hence only used for the upper 85 m of the 295 m sediment fill. Future core orientation designs that utilize both a magnetometer for HPC orientation and a gyro-

scope for extended shoe (non-rotating) coring could allow for the recovery of oriented cores to greater depths.

3. New Equipment: During the sediment-drilling program participants suggested several modifications to the GLAD800 system. One suggestion was to pump mud using hydraulic pumps run off the rig's generator instead of gasoline pumps. This modification would yield a quieter, cleaner working environment near the core-processing table. Hydraulic mud pumps also have the added benefit of fewer items requiring refueling. A second suggestion was to construct a mud recirculation system. Simply by guiding the mud that is discharged from the top of the casing every time a core is raised into a bladder in the moonpool, the mud could be saved and recirculated. Such a system would extend the mud supplies during coring as well as minimize the discharge of drilling mud into the lake at the lake surface. A third suggestion would be to have a mechanical wire guide that spools the anchor cable evenly onto the drum. Such a mechanical wire guide would keep people's hands away from the cable as it is being spooled in and thus minimize the chance of serious injury.
4. Coring Tools: At Bosumtwi, sediment corers were drilled to greater subbottom depths than in previous GLAD lake drilling projects. To be specific, the HPC corer was used to about 85 m blf, the extended shoe (non-rotating) to 243 m blf, and the extended core bit (rotating) to 295 m blf. Changes in corer type occurred as sediment compaction and bit weight warranted. Limitations encountered with the corers have been relayed to the manufacturer so that modifications can be made before their use in future drilling. In particular, the Extended Core Bit (Alien) corer produced undersized cores that are difficult to log accurately or to split and process. After modifying the spring at the corer head and water circulation at the bit with little success, it appears that more flexible core catchers (not available at Bosumtwi) may have yielded full diameter cores. Therefore, complete inventories of corer parts need to be onsite for each project. Lastly, the grease used on the corers is very likely to contaminate the sediment cores to the point where biomarker studies may be compromised. An assessment of the use of drilling grease (i.e., pipe dope) and ways to minimize its contact with sediment would aid future detailed studies of organic chemistry.
5. Downhole gamma logger. Based on experiences at Bosumtwi crater lake and recently at Lake Qinghai, ICDP likely needs to invest in a cheap, downhole gamma logger that can stay with the DOSECC corers/tool shack with "easy to follow" directions. This system would back up or replace the more high-tech GFZ system that requires technicians. A simple downhole logger will make it efficient and fast to

obtain much needed records, especially went drilling difficulties could benefit from immediate logging through casing.

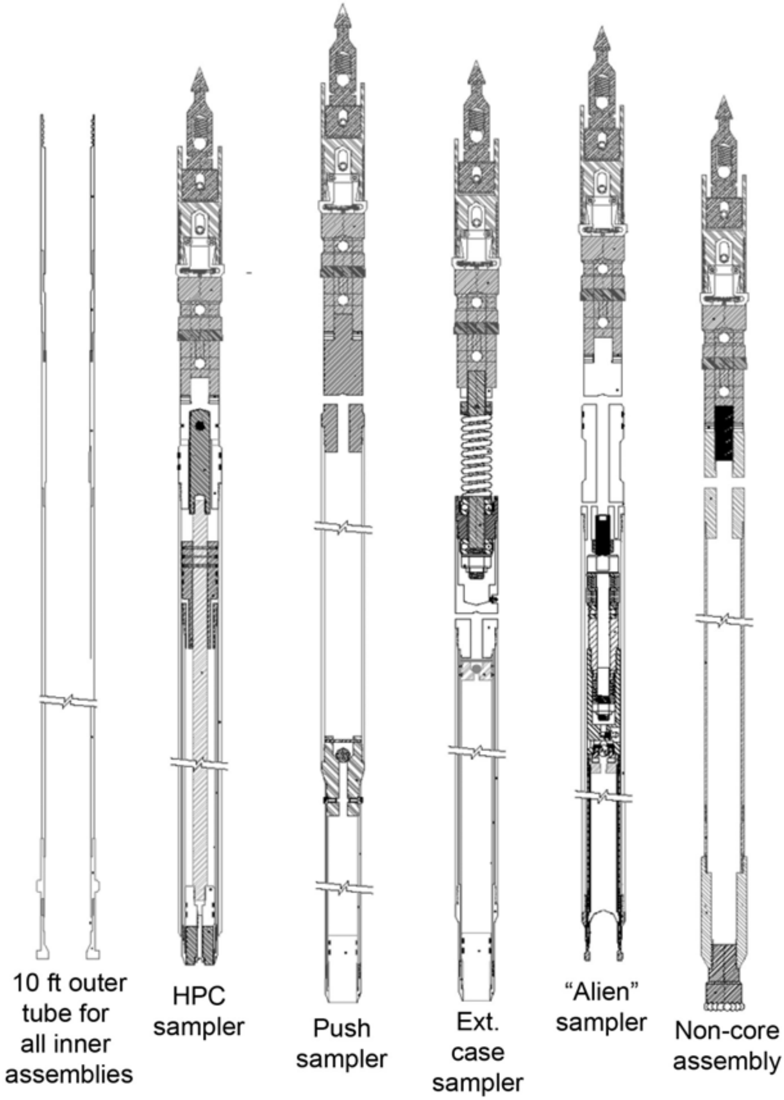

Fig. 13. Shown are the usual tools used for drilling lake sediments. From left to right, these include, a 10-foot outer tube used with all inner assemblies, a hydraulic piston core (HPC) sampler, Shelby tube "push" sampler, an extended nose, non-rotating (EXN) sampler, an extended core bit, rotating ("the Alien") sampler, and finally the non-sampling core assembly.

8.3 New Science Tools and Proxies

8.3.1 Scanning Core Loggers and Image Analysis

The analysis of lacustrine sediments is usually performed at a much higher resolution than marine sediments, because (1) the sedimentation rates are usually one order of magnitude higher, (2) the sediments are usually less subject to bioturbation, and (3) the core may record temporal variability that may be correlated with regional climate fluctuations. Therefore, drilling long sequences in lacustrine sediments presents the practical challenge of performing a large number of analyses on the cores to better resolve time in lacustrine deposits. However, new tools are now available for use by the ICDP community.

Scanning core loggers. Traditionally, sediment parameters have been measured on discrete samples obtained with the spatial subsampling resolution of only several centimeters (Zolitschka et al. 2001). New logging instruments, however, are now capable of carrying out rapid, continuous, non-destructive and high-resolution analyses of the physical and chemical sediment properties. These logging instruments incorporate a wide variety of detectors that are increasingly sensitive, fast and capable of working on smaller surface areas. They include, but are not limited to, magnetic susceptibility, gamma-ray density, P-wave velocity, spectrophotometry in several ranges of the spectrum, and computerized tomographic imaging. X-ray micro-fluorescence scanning systems have been recently developed and provide continuous and qualitative determination of the bulk elemental composition at resolutions varying from 0.05 mm to 1 cm. The results obtained from these instruments provide a rapid guideline for further subsampling strategies and allow comparison between cores from a single site. They also provide the direct measurement of valuable environmental proxy data. For instance, magnetic susceptibility can be regarded as a proxy for the mineralologic composition of the sediment and hence can be used as a powerful paleoclimate indicator (Williams et al. 1996). XRF-microfluorescence measurements of titanium have been used successfully to infer variations in the hydrological cycle in high sedimentation-rate marine basins (Haug et al. 2001). These loggers should be used systematically in all future ICDP cores.

Image analysis. Image analysis is a low cost but high-resolution analytical method that allows sediment cores to be studied at the sub-millimeter resolution necessary to resolve the detailed history contained in lake sediments. Image analysis is concerned with the extraction of quantitative sedimentological information from images captured in digital form. Paleoenvironmental studies of sediments, in particular, can greatly benefit from image analysis techniques. These techniques allow one to capture a wide range of visual data from images acquired at macroscopic scale (surface of sediment cores) and microscopic scale (thin-section, microfossil slides) using different regions of the electromagnetic spectrum (visible, UV, IR, X-Ray). Visual data include the counting of laminations (to develop age models), measurement of lamination thickness, and the establishment of sediment physical and chemical properties from color. For example, these techniques can be used to collect physical data such as the morphometry of microfossils (diatoms and coccoliths), grain size, grain morphometry, sediment fabric and sediment density. Chemical and mineralogical data can be inferred from images of related tools such as X-radiography, core scanning, non-normal scanning, and optical and electron microscopy.

To allow for quantified reconstructions, data obtained from images must be calibrated (Nederbragt and Thurow 2004) and tested for robustness (Francus and Pirard 2004). Once quantitative relationships are established between the sedimentary record and climate, image analysis can greatly contribute to a better understanding of past climate variability. For instance, measurements of grey-scale change from X-radiographs along a varved sequence from Finland (Fig. 14), provided quantified information regarding the seasonal accumulation of the annual minerogenic influx later correlated to spring runoff (Ojala 2004). A second example is provided by Jin et al. (2006) who measured the color of lacustrine sediments to evaluate weathering within a watershed.

Many image analysis applications are already available to process long lacustrine sedimentary sequences. New imaging systems that automate the acquisition and processing of images are under development (e.g., Bollmann et al. 2004; Seelos and Sirocko 2005) will soon be available. Among them is the development of a variety of imaging systems to automatically recognize microfossils, or measure grain-size from thin-sections. However, it is necessary to comprehensively compile metadata related to the imaging procedure in order to ensure the comparison and reproducibility of results (Francus et al. 2004). Core repositories should establish databases for these data.

Both scanning and imaging techniques allow the investigation of paleoenvironmental variability as recorded and preserved in lake sediment at high resolution and it is expected that these data will shed new light on the climate forcing mechanisms. Time resolution of this magnitude was not possible before with standard methods of discrete sampling.

The TEX86 paleothermometer. Understanding the role of temperature in continental climate dynamics over millennial and longer timescales is relatively limited, primarily due to the previous lack of a quantitative continental paleothermometer that could be trusted and independent of hydrological influence. Temperature is an important component of the climate system because it drives atmospheric and oceanic circulation. In the low to mid-latitudes, temperature gradients drive monsoonal circulation systems, which are a major, and often primary, source of precipitation. Gaining a better understanding of the role of temperature in the hydrologic cycle can provide essential information for climate modeling.

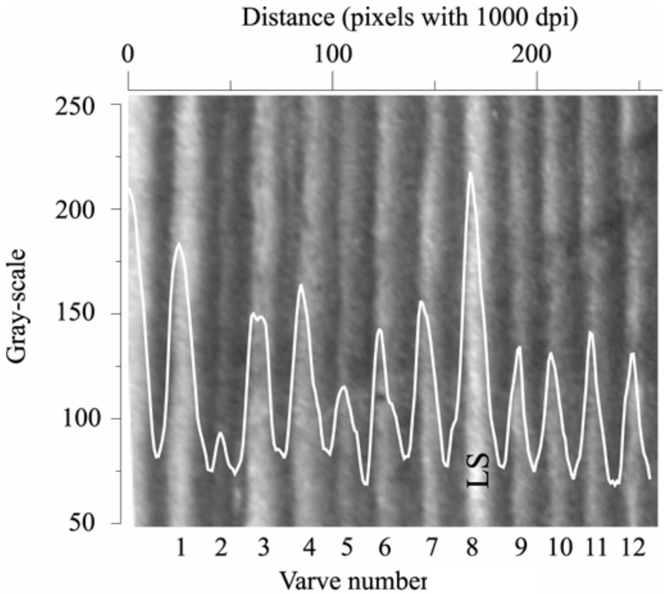

Fig. 14. A line-scan digital image analysis of Lake Nautajärvi clastic-organic varves. The density curve provides information on the seasonal accumulation of minerogenic material when separated by varve boundaries and treated statistically. LS = an annual accumulation of mineral matter (modified from Ojala 2004).

TEX_{86} (Schouten et al. 2002) was originally developed as an organic geochemical tool for determining sea surface temperatures from marine sediments. The index is based on the relative abundance of tetraether membrane lipids (glycerol dialkyl glycerol tetraethers, or GDGTs), produced by aquatic Crenarchaeota (Domain Archaea). Recent work has shown that GDGTs are well-preserved in the sediments of many large lakes. Further, TEX_{86} shows great promise as a robust independent paleothermometer for lacustrine systems (Powers et al. 2004). The TEX_{86} paleothermometer may be applied to reconstruct high-resolution records of past continental temperatures from globally distributed, climatically diverse large lakes (Powers et al. 2005). Moreover, TEX_{86} is a unique tool because it appears to be solely dependent upon growth temperature and not confounded by other environmental or biological effects such as changes in water chemistry or growth rates.

Large lakes are regional integrators of climate over the broad expanse of their drainage basins, and the TEX_{86} signal derived from the sediments of these lakes may well provide the most accurate quantitative and high-resolution estimate of past temperature on the continents. In the development of short-term climate models, continental paleotemperature data may be better for predicting abrupt climate events, as the continents do not have as much thermal inertia as the world oceans, and most lake sediment records have much higher temporal resolution than marine records.

Biomarkers and compound specific isotope analyses. Molecular biomarkers are a powerful tool to decipher preservation versus production issues routinely encountered in interpreting the total organic matter content of lacustrine sediments. As such, they can be excellent indicators of in-situ versus external production as well as indicators of diagenesis and changing sedimentary chemical conditions. Additionally, molecular biomarkers can provide information regarding the source of organic matter, which can then be linked to regional paleoenvironmental changes. In lacustrine sediments, organic matter typically consists of material produced within the lake, terrestrial inputs, and bacterial production from within the water column and sediments. The relative importance of each of these sources is controlled by a number of factors that are climatically dependent, including nutrient supply, light intensity, and water column overturn. Additionally, the preservation of sedimentary organic matter is dependent upon climate since water column stratification, temperature, and salinity affect the preservation of sedimentary organic matter.

Isotopic analyses of these biomarker compounds can provide even more specific information. For example, the $\delta^{13}C$ of specific biomarkers found in lake sediments can be used to determine sources of organic matter, past rates of primary productivity, and changes in surface water nutrient availability as well as determining different metabolic pathways of the source organisms. These tools are especially useful in examining changes in regional vegetation due to changes in temperature and aridity. Hydrogen isotopic compositions of compounds such as fatty acids have been shown to be excellent indicators of hydrologic changes in the watershed. These types of analyses will result in a more concrete understanding of the effects of climate on vegetation changes and allow decoupling of the effects of temperature versus aridity on these processes.

9 International Considerations for Future Lake Drilling

One of the many considerations surrounding the future of lake drilling is the notion that the science community expects core materials to be safely archived for further analysis for a reasonable number of years to come. This requires proper core storage at national facilities such as LacCore, University of Minnesota, USA (http://lrc.geo.umn.edu/LacCore/laccore.html) or the Alfred Wegener Institute, Germany. Moreover, it is critical that policies be developed to ensure the funding and standardization of initial core descriptions so that all cores receive basic analytical work. It is suggested that ICDP could take a leading role working with national core repositories to ensure uniform standards. Moreover this effort should also explore the notion of developing a common international core database, to be shared among facilities so that materials are widely accessible for study. The science community encourages national and international funding agencies to remember that cost-effectiveness for drilling is best evaluated in concert with the expectation that future proposals to work on such archived materials will be welcomed by national funding agencies.

10 Summary

Uncertainties in the climatic and environmental future of our planet continue to propel scientific investigation of the natural drivers of past climate and global change. Without a doubt, the natural history of post-glacial times commonly pursued by inexpensive coring lacks the full dynamic range of decadal to millennial scale events that allow us to better understand glacial/interglacial change, climate cycles implicated in many of the major parts of the Earth systems (e.g., Hadley Cell circulation and monsoons), as well as the linkages and phasing of ocean/atmosphere interactions. Continental archives obtained by deep drilling provide key records of hydrologic and climatic responses for comparison with ocean and ice core records and for model/data validation experiments.

Based upon the successes and lessons of lake drilling projects carried out over the first decade of the ICDP, the goal of the next decade should be to pursue the drilling of a network of sites aimed at capturing long climate-proxy records that trace critical, yet poorly understood aspects of natural climate dynamics. Some sites may also be pursued where the rationale can be made for understanding depositional records and proxies with respect to paleohydrology, drought frequency, paleoseismicity, hazards and extreme event stratigraphy where societies are threatened.

The development of international standards for initial core processing, treatment, and storage of lake cores remains a key necessity of concern. This is especially important so that future workers can continue to study existing cores at the pace of emerging technologies and proxies for decades to come. Such a well-planned insurance policy will make certain that we maximize the investments committed to scientific lake drilling.

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Continental Drilling and the Study of Impact Craters and Processes – an ICDP Perspective

Christian Koeberl[1] and Bernd Milkereit[2] *

[1]Department of Geological Sciences,
University of Vienna, Althanstrasse 14, A-1090 Vienna, Austria
e-mail: christian.koeberl@univie.ac.at (corresponding author)

[2]Department of Physics
University of Toronto, 60 St. George Street,
Toronto, Ontario M5S 1A7, Canada

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Abstract

Currently about 170 impact craters are known on Earth; about one third of those structures are not exposed on the surface and can only be studied by geophysics or drilling. The impact origin of geological structures can only be confirmed by petrographic and geochemical studies; thus, it is of crucial importance to obtain samples of subsurface structures. In addition, structures that have surface exposures commonly require drilling and drill cores to obtain information of the subsurface structure, to provide ground-truth for geophysical studies, and to obtain samples of rock types not exposed at the surface. For many years, drilling of impact craters was rarely done in dedicated projects, mainly due to the high cost involved. Structures were most often drilled for reasons unrelated to their impact origin. In the former Soviet Union a number of impact structures were drilled for scientific reasons, but in most of these cases the curation and proper care of the cores was not guaranteed.

More recently the International Continental Scientific Drilling Program (ICDP) has supported projects to study impact craters. The first ICDP-supported study of an impact structure was the drilling into the 200-km-diameter, K-T boundary age, subsurface Chicxulub impact crater, Mexico, which occurred between December 2001 and February 2002. The core retrieved from the borehole Yaxcopoil-1, 60 km SSW from the center of the structure, reached a depth of 1511 m and intersected 100 m of impact melt

breccia and suevite, which has been studied by an international team. From June to October 2004, the 10.5 km Bosumtwi crater, Ghana, was drilled within the framework of an ICDP project, to obtain a complete 1 million year paleoenvironmental record in an area for which only limited data exist, and to study the subsurface structure and crater fill of one of the best preserved large, young impact structures. From September to December 2005, the main part of another ICDP-funded drilling project was conducted, at the 85-km-diameter Chesapeake Bay impact structure, eastern USA, which involved drilling to a depth of 1.8 km. In 2008, it is likely that the El'gygytgyn structure (Arctic Russia) will be drilled as well. So far only few craters have been drilled – not enough to gain a broad understanding of impact crater formation processes and consequences.

In this chapter we summarize the current status of scientific drilling at impact craters, and provide some guidance and suggestions about future drilling projects that are relevant for impact research. Points we cover include: what is the importance of studying impact craters and processes, why is it important to drill impact craters or impact crater lakes, which important questions can be answered by drilling, which craters would be good targets and why; is there anything about the impact process, or of impact relevance, that can be learned by drilling outside any craters; what goals should be set for the future; how important is collaboration between different scientific fields? In the following report, we first briefly discuss the importance of impact cratering, then summarize experience from past drilling projects (ICDP and others), and finally we try to look into the future of scientific drilling of impact structures.

1 Introduction: Impact Processes

Impact processes are among the fundamental mechanisms that have formed and shaped the Earth and our planetary system. Impacts and related developments have changed the Earth through geological time and have been key factors in the development of life on our planet.

The recognition of interplanetary collisions and the formation of impact craters on planetary surfaces as a fundamental geological process has led to a new paradigm in terrestrial geology: The geological and biological evolution of Earth is not only influenced by internal or superficial geological processes, but also by external, highly energetic processes. Hypervelocity impacts have produced, on a time scale of minutes, deep scars in the Earth's crust and mantle, which can be up to several thousand kilometers wide. On Earth, we currently know 174 impact structures – see Fig. 1. For a list of currently proven craters, including information and literature, and updates on crater discoveries, see the Canadian "Earth Impact Database" at: http://www.unb.ca/passc/ImpactDatabase/. Most of the very large and old craters, which are still present on the Moon, have been erased on Earth due to internal geological processes on Earth, such as volcanism, tectonics, and weathering – i.e., the result of the active geosphere, hydrosphere, and atmosphere of the Earth. There are certainly more craters on Earth than those known today, but the total number preserved on Earth will fall far short of the hundreds of thousands that would be expected from the lunar impact cratering rate. Unlike Earth, the unaltered ancient surface of the Moon has acted as a reliable recorder of impact processes in the inner solar system over the past 3 to 4 billion years.

It is beyond any doubt that the study of impact craters on Earth is an absolute prerequisite for the understanding of some of the most fundamental problems of Earth and planetary sciences, including:

- variation of the morphology and structure of impact craters as a function of their size and of planetary gravity,
- origin, constitution, and evolution of the Archean crust of the Earth,
- origin and evolution of early primitive life,
- discontinuities in the evolution of later complex life (i.e., Phanerozoic mass extinctions).

A major topic of impact research is the effect on the global environment and possible relations to mass extinctions. At present, the Chicxulub impact structure, with a Cretaceous-Tertiary (KT) boundary age, is the only one for which a relationship to a major mass-extinction event has been established, at least with respect to the timing. To explore and demonstrate the potentially important role of meteorite impacts on biotic extinctions and subsequent evolution, it is important to find other examples of a meteorite impact that is related to a mass extinction.

In addition to this biological interest, the study of meteorite impact craters also has an important economical aspect. Some of the Earth's important mineral deposits (Ni-Cu-Pt mines, Sudbury Structure, Canada) and hydrocarbon reservoirs (the giant Cantarell oil field, Chicxulub structure, Mexico – the 8th largest oil field in the world) are closely associated with large impact events.

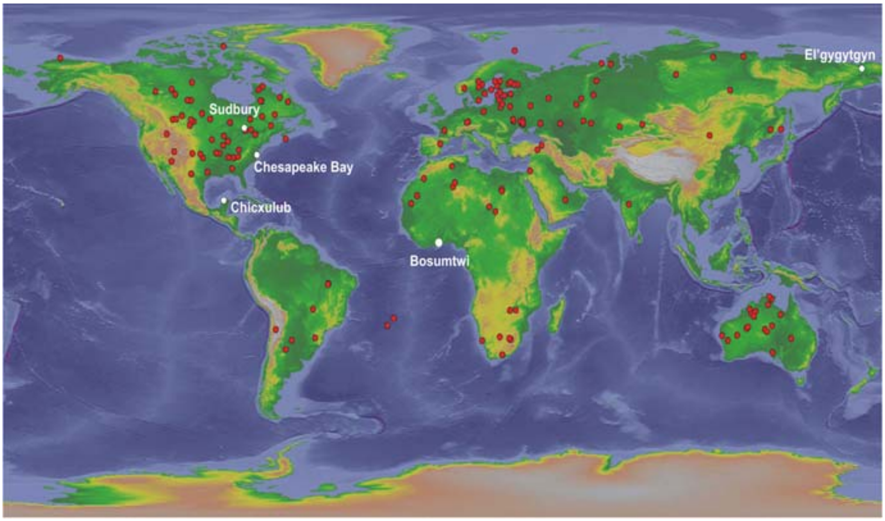

Fig. 1. Location map of meteorite impact crater (status 2006) with current and proposed ICDP projects (source: http://www.unb.ca/passc/ImpactDatabase/).

2 Impact Craters and Shock Metamorphism

This section provides a short introduction to the importance and characteristics of impact structures (mostly following reviews by Koeberl 2001, 2002; Koeberl and Martinez-Ruiz 2003; as well as Koeberl and Reimold 2005).

All bodies in the solar system - planets, moons, asteroids, etc. - that have solid surfaces are covered by craters. In contrast to many other planets and moons in the solar system, the recognition of impact craters on the Earth is difficult, because active geological and atmospheric processes on our planet tend to obscure or erase the impact record in geologically short times. Impact craters can only be recognized from the study of their rocks – remote sensing and geophysical investigations can only provide initial hints at the possible presence of an impact crater. Petrographic studies of rocks at impact craters can lead to the confirmation of impact-characteristic shock metamorphic effects, and geochemical studies may yield information on the presence of meteoritic components in these rocks. Craters of any type and morphology are not an obvious and common landform on Earth, due to erosion and sedimentation and other active geological processes. Considering that some impact events have demonstrably affected the geological and biological evolution on Earth (e.g., papers in Ryder et al. 1996; Koeberl and MacLeod 2002), and that even small impacts can disrupt the biosphere and lead to local and regional devastation (e.g., Chapman and Morrison 1994), the understanding of impact structures and the processes by which they form should be of interest not only to Earth scientists, but also to society in general.

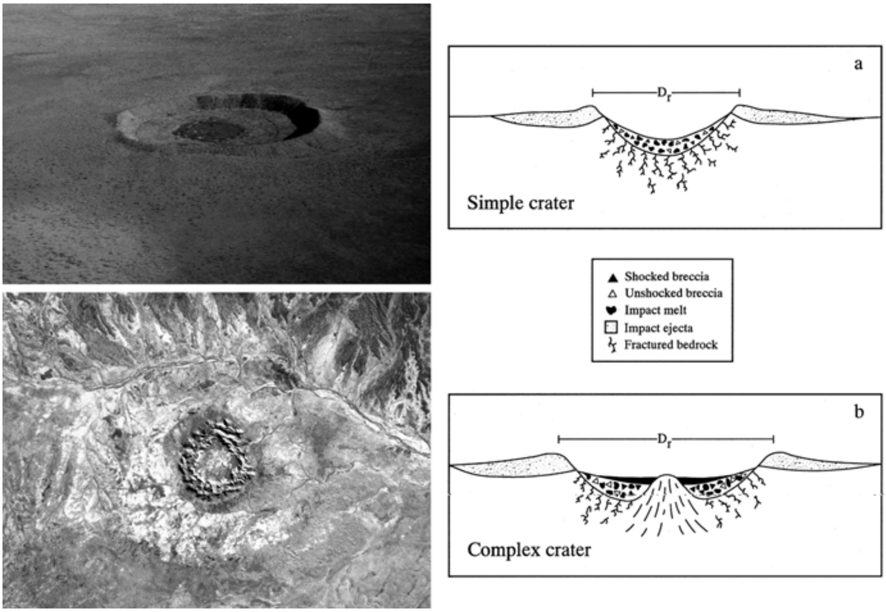

Fig. 2. Simple and complex craters **a.** the 1 km diameter Wolf Creek crater is an example of a simple crater and **b.** the 24 km diameter Gosses Bluff structure is an eroded complex crater. Both are in Australia. Cross sections are shown to illustrate the crater fill.

In terms of morphology, an unaltered and uneroded feature is called an "impact crater", whereas a more eroded or filled-in feature is called an "impact structure". Impact craters occur on Earth in two distinctly different morphological forms. They are known as simple craters (small bowl-shaped craters) with diameters up to about 2 to 4 km, and complex craters, which have larger diameters (Fig. 2). Craters of both types have an outer rim and are filled by a mixture of fallback ejecta and material slumped in from the walls and crater rim during the early phases of crater formation. Such crater infill may include brecciated and/or fractured rocks, and impact melt rocks. Fresh simple craters have an apparent depth (crater rim to present-day crater floor) that is about one third of the crater diameter. For complex craters, this value is closer to one fifth or one sixth. Complex craters are characterized by a central uplift. The central structural uplift in complex craters commonly exposes rocks that are usually uplifted from considerable depth and thus contrast with the stratigraphic sequence of the environs around the impact structure. On average, the ratio of actual stratigraphic uplift to crater diameter amounts to about 0.1 (e.g., Melosh 1989). In complex craters the central uplift usually consists of dense basement rocks and usually contains severely shocked material. This uplift is often more resistant to erosion than the rest of the crater, and, thus, in old eroded structures the central uplift may be the only remnant of the crater that can still be identified.

Remote sensing and morphological observations may yield important initial data regarding the recognition of a potential impact structure (such as annular drainage patterns or topographic ring structures), but cannot provide confirming evidence. Geophysical characteristics of impact craters include gravity, magnetic and distinct reflection and/or refraction seismic signatures, electrical resistivity anomalies, and others (e.g., for a review see Grieve and Pilkington 1996). In general, simple craters have negative gravity anomalies due to the lower density of the brecciated rocks compared to the unbrecciated target rocks outside of the structure, whereas complex craters often have a positive gravity anomaly associated with the central uplift of dense rocks originally located lower in the Earth’s crust. This central positive gravity anomaly may be surrounded by an annular negative anomaly. Magnetic anomalies can be more varied than gravity anomalies (e.g., Henkel and Reimold 2002). The target rocks may have been magnetically diverse, but the impact event may also cause anomalies related to impact-induced remanence. Seismic investigations of impact structures commonly show the loss of seismic coherence due to structural disturbance, slumping, and brecciation. Such geophysical surveys are important for the detection of anomalous subsurface structural features, which may be deeply eroded craters or impact structures entirely covered by post-impact sediments. In the past few decades, a large number of impact structures have been identified in the course of geophysical and drilling surveys related to hydrocarbon and other economic exploration (Grieve and Masaitis 1994; Reimold et al. 2005).

Only the petrographic and geochemical study of actual rocks from the potential impact structure will bring final confirmation of the presence of an impact structure. In case of a structure that is not exposed on the surface, drill-core samples are essential. Good materials for the recognition of an impact origin are various types of breccia and melt rocks. These rocks often carry unambiguous evidence for the impact origin of a structure in the form of shocked mineral and lithic clasts or a contamination from the extraterrestrial projectile.

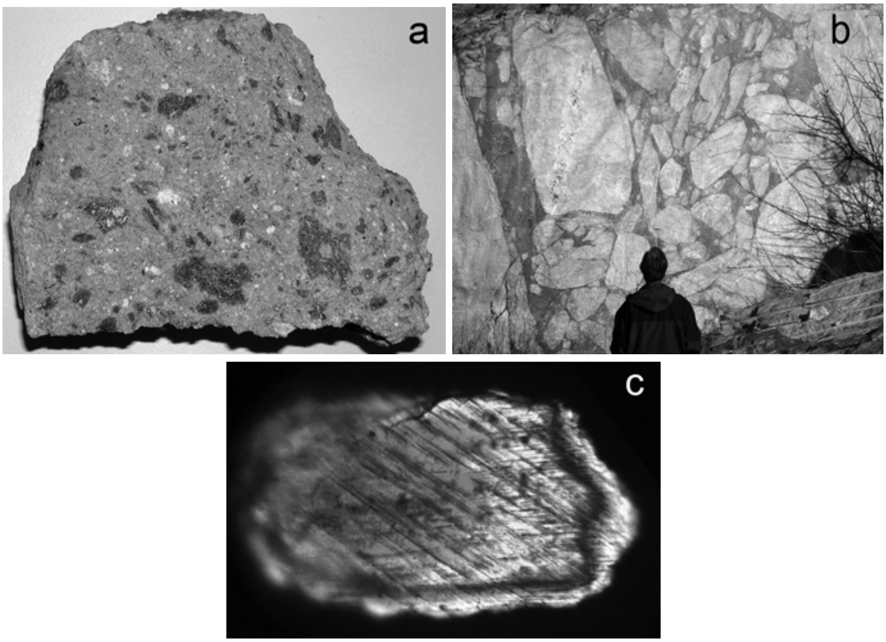

Fig. 3. Variety of products of shock metamorphism.
a. Suevitic breccia from the Aumühle quarry at the Ries crater, southern Germany. Width of specimen ca. 20 cm. The dark frothy areas are impact glass that is included in the polymict breccia (photo by C. Koeberl).
b. Pseudotachylitic breccia vein, ca. 2.5 m wide, at the Leuukop Hill quarry, Vredefort impact structure, South Africa (photo by C. Koeberl).
c. Shocked quartz grain (120 μm long dimension) from distal ejecta found in SE South Dakota (USA), derived from the Manson impact structure (Iowa, USA; see Katongo et al. 2004). The grain shows two well-developed sets of closely spaced planar deformation features (PDFs), which are uniquely characteristic of shock pressures associated with hypervelocity impact events (photo by C. Katongo).

The impact-crater fill consists of a variety of monomict and polymict breccia types (for definitions see Stöffler and Grieve 1994; French 1998). For the identification of meteorite impact structures, suevites (a polymict, melt-bearing breccia) and impact melt breccias (or impact melt rocks) are the most commonly studied units. In cases of very deeply eroded structures, only remnants of injected impact breccias in the form of veins or dikes may remain. Besides injections of suevite and impact melt rock, and local (in situ) formations of monomict or polymict clastic impact breccia, veins and pods of so-called “pseudotachylitic breccia” have been observed at a number of impact structures (Fig. 3b). This material may closely resemble what is known as “pseudotachylite,” the term for “friction melt”, and indeed has been referred as this extensively in the literature. However, it has become clear in recent years that not all of the formations of such appearance actually represent friction melt, but also include impact melt rock and even tectonically produced fault breccias (friction melt, mylonite, or cataclasite). Thus, it is prudent to verify the nature of any such material before labeling it with a genetic lithological term (Reimold and Gibson 2005).

The presence of shock metamorphic effects constitutes confirming evidence for impact processes. In nature, shock metamorphic effects are uniquely characteristic of shock levels associated with hypervelocity impact. These effects are best studied in the various breccia types that are found within and around a crater structure, as well as in the formations exhumed in the central uplift area. During impact, shock pressures of ≥100 GPa and temperatures ≥3000°C are produced in large volumes of target rock. These conditions are significantly different from conditions for endogenic metamorphism of crustal rocks, with maximum temperatures of 1200°C and pressures of usually <2 GPa. Shock compression is not a thermodynamically reversible process, and most of the structural and phase changes in minerals and rocks are uniquely characteristic of the high pressures (diagnostic shock effects are known for the range from 8 to >50 GPa) and extreme strain rates (up to10^8 s^{-1}) (for comparison: a bat hitting a baseball generates a strain rate of ~10^2/s) associated with impact. The products of static compression, as well as those of volcanic or tectonic processes, differ from those of shock metamorphism, because of peak pressures and strain rates that are lower by many orders of magnitude.

A wide variety of shock metamorphic effects have been identified. The most common ones include planar micro-deformation features, optical mosaicism, changes in refractive index, birefringence, and optical axis angle, isotropization (e.g., formation of diaplectic glasses), and phase changes (high pressure phases; melting). Kink bands (mainly in micas) have also been described as a result of shock metamorphism, but can also be the result of normal tectonic deformation (for reviews, refer to, for example, Stöffler and Langenhorst 1994; Grieve et al. 1996; French 1998).

Planar microstructures are the most characteristic expressions of shock metamorphism and occur as planar fractures (PFs) and planar deformation features (PDFs) (Fig. 3c). The presence of PDFs in rock-forming minerals (e.g., quartz, feldspar, or olivine) provides diagnostic evidence for shock deformation, and, thus, for the impact origin of a geological structure or ejecta layer (e.g., see Stöffler and Langenhorst 1994; Montanari and Koeberl 2000, and references therein). Planar fractures, in contrast to irregular, non-planar fractures, are thin fissures, spaced about 20 µm or more apart. While they are not considered shock diagnostic, per se, should they be observed in significant abundance and particularly relatively densely spaced sets of multiple orientations, they can provide a strong indication that shock pressures around 5-10 GPa were present. To an inexperienced observer, distinguishing "true" PDFs from other lamellar features (fractures, fluid inclusion trails, and/or tectonic deformation bands) is not always easy.

The detection of small amounts of meteoritic matter in breccias and melt rocks can also provide confirming evidence of impact, but it is extremely difficult to do this (see Koeberl 1998 for a review). Only elements that have high abundances in meteorites, but low ones in terrestrial crustal rocks are useful, for example, the siderophile platinum-group elements (PGEs; including Ru, Rh, Pd, Os, Ir, and Pt) and other siderophile elements (e.g., Co and Ni) are commonly studied in this regard. Elevated siderophile element contents in impact melt rock or melt-rich suevite, compared to target rock abundances, can be indicative of the presence of either a chondritic or an iron meteoritic component. Achondritic projectiles (stony meteorites that underwent magmatic differentiation) are much more difficult to trace, because they have significantly lower abundances of the key siderophile elements. It is also necessary to sample all possible target rocks to determine the so-called indigenous component (i.e., the contribution to the siderophile element content of the impact melt rocks from the target). This analysis allows us to ascertain that no siderophile element-rich, mantle-derived target rock has remained undetected. So far, meteoritic components have been identified for just over 40 impact structures out of the more than 170 impact structures currently identified on Earth.

3 Previous Drilling Efforts at Impact Craters

Of the 174 individual terrestrial impact structures (number listed as of September 2006; see http://www.unb.ca/passc/ImpactDatabase/ - although the evidence for a few of those listed is not very strong) and other small crater fields currently identified, about half have been drilled in some way or another, although this does not mean that cores were obtained, that drill cores are preserved anywhere for study, or that that the drilling was documented and published. Of those that were drilled, the majority are not exposed on the surface (i.e., they are buried by post-impact sediments or completely/partially underwater). The initial motivation to drill these structures was either scientific or economic. Drilling was accomplished in order to: (1) confirm the presence of an impact structure and to learn about the physicochemical processes involved through the study of crater geology;

and (2) satisfy economic geological interests, such as exploration for hydrocarbons in structural traps. The economic motivation has largely been potential recovery of commercial quantities of hydrocarbons. In fact, the initial discovery of buried impact structures is commonly due to geophysical and structural anomalies in sedimentary basins under exploration. Indeed, the potential to discover producible quantities of hydrocarbons at terrestrial impact structures is relatively high in sedimentary basins known to contain hydrocarbons, e.g., in North America, approximately 50 % of the known impact structures in hydrocarbon-bearing basins have commercial oil and/or gas fields (Grieve 2005).

Drilling in impact craters started as early as the beginning of the systematic study of craters in the 1950s by Canadian astronomers and geologists. Scientific drilling of craters has been restricted to a few countries where special interests had been developed such as Canada, the former Soviet Union (USSR), USA, Germany, Sweden, and others. The target craters and the drilling sites were usually not identified as the result of a systematic evaluation of an international community of experts on impact research, but were rather selected on the basis of local decisions, sometimes governed by economic interests (ore deposits in the Sudbury structure in Canada and impact diamonds in Russia). For these reasons and because of problems with the maintenance of the drill cores, many of the pre-ICDP bore holes are of rather limited scientific value. In spite of these limitations, the well-planned and systematic studies of drill cores in some Canadian craters (e.g., Clearwater Lakes, Manicouagan, Mistastin, and Carswell), some Russian craters (e.g., Popigai, Boltysh, and Puchez-Katunki), the German craters (Ries and Steinheim), the Swedish Siljan crater, and some others established the basis for a rather advanced model for the origin of the simple and complex terrestrial crater. This model addressed the composition, distribution and origin of different types of impact formations (allochthonous and autochthonous breccias) as well as the modern principles of shock metamorphism of rocks and minerals (see previous section). Comprehensive studies of specific impact craters, including scientific drilling, revealed some universal principles about terrestrial impact craters. These include:

1. Independent of the size of the impactor, all craters develop a so-called transient cavity (deep, parabolically shaped crater), the excavation of which leads to the formation of a continuous ejecta blanket around the crater and to discontinuous distal ejecta. Depending on its size (and on the gravity of the planet) the transient cavity is modified in a highly dynamic process to form (with increasing size):
   - simple craters, bowl-shaped,

   - complex craters with central uplift,
   - complex craters with inner ring (peak ring), and
   - complex craters with multiple rings.
2. Complex craters result from the collapse of the transient cavity in a quasi-hydrodynamic process (possibly due to acoustic fluidization) forming a central uplift which itself collapses in larger complex craters to form a peak ring and eventually additional rings.
3. In complex craters, a central, upward rising ejecta plume of vaporized rock, melt, and solid fragments develops and collapses on a time scale of minutes to hours, which forms suevitic breccias on top of the parautothonous breccia lens inside the crater and on top of the inner part of the ejecta blanket. With increasing size of the impact structure (craters > ca. 100 km), the material of the ejecta plume rises beyond the stratosphere and is globally distributed.

4 Some Specific Examples of Crater Drilling before ICDP

Several impact structures have been investigated in the past through drilling programs – with and without coring efforts. One of the earliest impact-related drilling programs must have been the unsuccessful attempts by D. M. Barringer (between about 1905 and 1928) to find the remains of the iron meteorite thought to lie beneath Barringer Crater in Arizona. In the 1950s, a program to drill several Canadian craters started, and soon thereafter extensive crater-drilling projects commenced in the Soviet Union (see below). Other craters at various locations in the world were also drilled for various reasons and with varying success. The deepest wells - without coring - were drilled within the Siljan ringed structure in Sweden (Boden and Eriksson 1988) in order to check the presence of a presumed large-scale deposit of abiotic hydrocarbons, which were never found.

4.1 Past Drilling at Impacts in Canada and the former Soviet Union

Of the 29 impact structures currently known in Canada, 62 % have been drilled (Appendix 1). This figure is somewhat higher than globally because all known impact craters in the western Canada Sedimentary basin, as well as several other Canadian craters, were drilled for economic purposes. Only seven Canadian impact structures were drilled exclusively for scientific purposes. Most of these were part of a campaign to identify impact structures in Canada, which was started in the late 1950s by the Dominion

Observatory. Drilling continued until the late 1960s and, over that time period, a total of ~11 km of impact-crater core was obtained.

The values given above for Canadian craters can be compared to the estimated 25 impact structures (~ 66 % of the total sample) that were drilled within the territory of the former USSR, for which there appears to have been a scientific motivation. There are, however, major geologic differences between Canada and the former USSR, as platform sediments capable of burying impact structures overlie much of the crystalline basement in the latter. In addition, all drilling of such structures during this time is considered to be, at least, quasi-scientific due to the nature of the political infrastructure and lack of independent commercial companies in the former USSR. Some of the state-sponsored drilling was motivated by the economic factors, such as the search for impact diamonds in the 100 km-diameter Popigai structure.

At the time of drilling of Canadian impact structures, emphasis was on obtaining data, which could establish whether or not a particular structure had an impact origin. Once an impact origin was indicated few of the cores were logged or studied in detail, beyond the production of some generalized cross-sections (e.g., Dence et al. 1968). Most Canadian drilling occurred during a time when the knowledge of impact processes was relatively rudimentary and the focus was on first-order processes. In fact, the same lack of published detail on cores and cross-sections also applies to impact structures drilled during the same period in the territory of the former USSR (Masaitis 1999). There are, however, a few exceptions. For example, in Canada, detailed studies were carried out on core from the West Hawk structure (Short 1970) and the composite and detailed subsurface character provided by the ~ 5 km of core from Brent structure was fundamental in defining the nature of simple craters in the third dimension and in introducing the concept of the “transient cavity” (Dence 1968).

Apart from post-drilling measurements of physical properties of cores such as density and magnetic susceptibility, which have been carried out only in a few cases, no significant continuous geophysical measurements, e.g., down-hole logging, were made at these drill holes because of the lack of appropriate technology at the time. Although the drilling was not generally designed to address specific scientific issues related to impact processes, some of the cores from Canadian craters have been re-examined more recently in light of specific questions and with more modern analytical technologies (e.g., Hische 1994). The value of many of these cores has been enhanced by their preservation and storage largely in a single location (Appendix 1).

Unfortunately, this is not the case for cores from craters in the former USSR. These cores commonly remained the responsibility of local authorities and, in some cases, the core was unprotected at the drill site (e.g., Popigai) or was otherwise lost (V. Masaitis, pers. comm. 2006; E. Gurov, pers. comm. 2006). Several impact structures in the former Soviet Union were investigated with the help of drilling programs (see Appendix 2 for details). Drilling was designed to explore mineral deposits and in many cases was not designed to gain data that later established the nature of these structures. Where the impact origin of a structure was confirmed, however, drilling was performed with specific goals, e.g., deep mapping, delineation of structural features, or sampling of ore-bearing formations. Nevertheless, some more modern interpretations have been carried out on material and core samples in institutional collections in Russia (e.g., Masaitis 1998; Whitehead et al. 2002). The most spectacular drilling effort in Russia was at the 40 km-diameter Puchezh-Katunki crater, where (besides some shallower holes) a deep drill core to a depth of almost 5.4 km was drilled (see next section).

In summary, while a lot of effort and money was put into drilling at various craters, the cores are mostly lost, not well curated, or simply have not been studied or documented to the standards of today. Correlated geophysical studies were almost absent.

4.2 Specific Examples of Drilled Craters

Some descriptions and results of drilling projects at various impact structures that were drilled over the past decades are briefly summarized in this section. The selection given here is biased towards structures for which easily accessible published literature exist, and is by no means comprehensive. Many other impact structures were drilled without the intent of specifically studying an impact structure, for example, as a by-product of regional exploration, water-well drilling, or commercial hydrocarbon exploration, to name just a few. In most of these cases, no core or only very limited cores were collected. In some instances, drill cuttings might have been preserved, which would allow for the detection of impact-related effects, e.g., the case of Red Wing Creek (see Koeberl et al. 1996).

Brent (Ontario, Canada; N 46° 5'; W 78° 29'): This 450 Ma-old impact crater, originally 3.8 km in diameter, was drilled by the Geological Survey of Canada in the 1950s and 1960s. A series of boreholes into and through the crater fill, and in several instances extending into the crater floor, crossed the entire width of the crater structure thus allowing the construction of a continuous cross-section through the crater, and providing first comprehensive understanding of the 3D-structure of a small, bowl-shaped impact structure. At Brent, small impact melt bodies occur within a general crater fill of suevitic breccia (Grieve 1978). Through geochemical study, it was also possible to trace the elemental signature of the extraterrestrial projectile.

Ries (Germany; N 48° 53'; E 10° 37'): The Ries crater, with a current diameter of about 25 km, formed about 14.5 Ma ago in southern Germany in Triassic and Jurassic sediments overlying crystalline basement. For a recent review on the Ries, see the paper by Kring (2005). The Ries crater has been drilled in a number of locations, yielding several (mostly shallow) cores. For example, Hörz et al. (1983) studied nine cores (a total of 560 m of core material obtained 16 to 37 km from the crater center), which penetrate through the Bunte Breccia, a polymict impact breccia lying outside of the crater. Inside the crater, suevite lies below post-impact lake sediments, and is not exposed at the surface like the fallout suevite. However, three boreholes have been drilled into the deposits, the deepest of which is the 1973 Nördlingen borehole (Geologica Bavarica 1977), which reached a depth of ca. 1.2 km. This core revealed significant information on cratering mechanics and the order of deposition of crater fill breccias.

Ames (Oklahoma, USA; N 36° 15'; W 98° 12'): The 15-km-diameter Ames structure in northwestern Oklahoma is located in Cambro-Ordovician Arbuckle Dolomite, which is overlain by Middle Ordovician Oil Creek Shale. The feature is marked by two concentric ring structures, with the inner ring structure (about 5 km in diameter) thought to be the collapsed remnant of a central uplift. The inner ring is composed of brecciated Precambrian granites and Arbuckle Dolomite. Numerous wells, which are oil- and gas-producing, have been drilled in the crater rim and the central uplift areas, making Ames one of the more economically important impact structures of the world (e.g., see Johnson and Campbell 1997; Koeberl et al. 2001).

Vredefort (South Africa; S 27° 0'; E 27° 30'): The long controversial Vredefort Dome on the Kaapvaal Craton of South Africa was confirmed in the mid-1990s as being of impact origin (see review by Gibson and Reimold 2001). Modeling of Vredefort regional geophysics (Henkel and Reimold 1998) and scaling of deformation phenomena (Therriault et al. 1997) has since established that the entire Witwatersrand basin must be considered as the actual extent of this impact structure (Grieve and Therriault 2000) of a conservatively estimated 250-300 km original diameter. Drilling has obviously been an integral part of the gold mining operations throughout the Witwatersrand basin, but the focus of this work has been generally limited to economic aspects of this basin. Several very deep -- in excess of 4 or even 5 km depth -- commercial boreholes have been sunk by the gold-mining industry in the north-central parts of the Witwatersrand basin in attempts to extend the ore resources of the so-called Golden Arc (e.g., Robb and Robb 1998) towards the Vredefort dome in the center of the basin, thus providing information about the deepest part of the rim syncline around the central uplift. Undoubtedly, access to these boreholes would extend our knowledge about the deformation intensity between the exposed Vredefort dome and the goldfields of the Golden Arc along the outer flank of the syncline around the central uplift.

Three relatively shallow boreholes, up to 300 m depth, have been drilled in the most central part of the Vredefort Dome for purely scientific purposes, namely studies of deformation and metamorphism of the deepest level of the Kaapvaal crust exposed in the area of the strongly uplifted dome. The results have been diverse and there are multiple interpretations. One group favors an interpretation that one of these boreholes intersected upper mantle material, specifically that a dome-wide, Kibaran (1-1.2 Ga) sheet intrusion was intersected. In addition, much knowledge about shock and thermal deformation related to the impact event at this deep level of the central uplift has been obtained (see papers by Hart et al. 1990; Gibson and Reimold 2001, 2005).

Tswaing (South Africa; S 25° 24'; E 28° 5'): Tswaing (previously known as Pretoria Saltpan) is a ca. 200,000 year old simple, bowl-shaped impact crater, and at 1.3 km diameter is of comparable size to Barringer Crater (Fig. 4). Relative to Barringer, Tswaing is significantly more eroded, as it is four times as old. In 1988 a 200-m-deep borehole was drilled close to the center of the structure, to obtain a paleoclimatic record and to confirm the origin of the crater. Drilling was successful, as the crater fill provided a 200,000 year paleo-environmental record, and a suevitic breccia offered shock metamorphic evidence as proof of an impact origin for the crater.

Manson (Iowa, USA; N 42° 35'; W 94° 33'): In 1991 and 1992, the Iowa Geological Survey Bureau and U.S. Geological Survey began to investigate the possibility that the Manson impact was a Cretaceous-Tertiary (KT) boundary event. During the course of this investigation 12 research cores, totaling over 1.2 km of core, were obtained from all terranes of the crater. Study of those cores and other data by scientists throughout the United States and from several other countries produced an understanding of the processes involved in the formation of the Manson Structure. This investigation identified the Manson Structure as a "complex" impact crater; that is, it includes an outermost "terrace" of down-dropped blocks, an inner "central peak," and a "crater moat" in between. Important information not only on the age (not K-T boundary age), but also on cratering mechanics and on the deposition of different types, was gained from the drilling. Details of the Manson crater drilling project are given by Koeberl and Anderson (1996). Distal ejecta from Manson have been found in Nebraska and South Dakota (Fig. 3c; Katongo et al. 2004).

Fig. 4. Aerial view of Tswaing crater, South Africa (photo by W.U. Reimold).

Morokweng (South Africa; S 26° 28'; E 23° 32'): A 30 km-wide aeromagnetic anomaly had long been known in this part of the North West Province of South Africa, which is entirely covered under sediments of the Kalahari Group. Three boreholes into the central aeromagnetic anomaly were the basis of work carried out by Reimold et al. (1999) and Andreoli et al. (1999); see also Reimold et al. (2002). The three boreholes extend to depths of 130-271 m and intersected an impact melt body at depths between 36 and 115 m, with thickness between ca. 94 and 150 m (Koeberl and Reimold 2003). The melt body is strongly homogenized and carries a strong meteoritic component of 2-5 wt%, which is highly unusual as most impact craters show very little meteoritic material. This crater and its melt rock should be studied in more detail to learn more about the distribution of meteoritic material, particularly in view of the recent suggestion by Maier et al. (2006) that fragments of the asteroid may be preserved in the melt rock.

Puchezh-Katunki (Russia; N 56° 58'; E 43° 43'): Deep drilling in the ~165 Ma old Puchezh-Katunki impact structure, which is located in the European part of Russia, yielded the deepest core hole in any impact structure in the world. The Vorotilovo hole with a final depth of 5,374 m was drilled in the crystalline central uplift of this structure. The drilling of this deep hole, at 56° 58' N, 43° 43' E, commenced on 8 June 1989 and finished on 1 September 1992. The pilot well, 100 m to the north of the of the main hole site, ended at a depth of 1,498 m. Drilling of both wells was carried out with continuous coring and the total length of recovered cores was 3,082 m. Contemporaneously with drilling, comprehensive studies of the well, the borehole environment, and the cores were conducted. In addition, material of geological surveys and geophysical data from the previously drilled 151 holes, with depths of 500 to 1,000 m, were studied. About 40 wells, whose cores had been stored, were re-documented in order to re-interpret those well logs whose cores were lost and whose documentation was conducted without any study of the shock-metamorphic effects in these rocks. Details of this extraordinary drilling effort will be available in an updated translation of a Russian compilation (Deutsch et al. 2007).

Mjølnir (Barents Sea, offshore Norway; N 73° 48'; E 29° 40'): The 40-km diameter Mjølnir crater is a marine impact crater in the central Barents Sea. Geological data (supported by geophysical data) unequivocally confirm that a bolide impacted at ~142 Ma into an epicontinental basin with 300-500 m paleo-water depth (e.g., Dypvik et al. 1996). A total of ~2,100 km of seismic reflection profiles were collected and clearly image the impact-related and post-impact structure and stratigraphy. In addition, free-air gravity and seismic velocity anomalies exhibit a close correspondence to the impact-induced structure and physical property distribution. Two shallow boreholes, one near the center and another ~30 km inside/outside the crater periphery offer a detailed seismic stratigraphic correlation and confirm the impact origin of the structure (e.g., Tsikalas et al. 2002). The boreholes revealed brecciated sediments, which contained shocked quartz bearing abundant planar fractures/deformation features (Sandbakken 2002). There is also a prominent Mjølnir ejecta layer with an iridium abundance peak of about 1 ppb – about 15 times above the background level – and shocked quartz grains (e.g., Dypvik et al. 1996). These shallow boreholes provided tantalizing hints of what could be learned from drilling. More and deeper cores should be obtained in the future into this well-preserved marine-target impact structure, as it is an important example of a marine target.

5 ICDP Drilling Projects at Impact Craters

Drilling impact structures, or core-drilling related to the study of impact processes, has been one of the main scientific goals of the ICDP since its inception. Ten years ago, the drilling into the Chicxulub impact structure was one of the first recommended projects of the newly formed ICDP.

Since that time, three impact-related drilling projects have been performed within the auspices of (and with major financing by) ICDP (namely, Chicxulub, Bosumtwi, and Chesapeake Bay), and one more has been approved (El'gygytgyn). Several more impact-relevant projects are in the planning stage. This section provides short overviews of the three past and present ICDP-financed drilling projects at impact structures.

5.1 Chicxulub (Mexico)

Chicxulub, centered at N 21° 20' and W 89° 30' on the Yucatán Peninsula, México, is the world's third largest known impact structure (Grieve and Therriault 2004) on Earth. Its formation is widely accepted to have been responsible for the dramatic environmental changes at the Cretaceous-Tertiary (KT) boundary (e.g., Blum et al. 1993; papers in Ryder et al. 1996; and Koeberl and McLeod 2002). The most recently drilled core from the structure, Yaxcopoil-1 (Yax-1 in Fig. 5), was retrieved by the International Continental Drilling Program (see Dressler et al. 2003, 2004). Decades ago PEMEX, the Mexican National Oil Company, had drilled the Chicxulub gravity low for oil exploration purposes. Some of the cores were preserved and their study provided a glimpse of the crater lithology. The C-1 well lies near the central uplift of the crater, Y-6 in the peak ring, approximately 50 km SW of C-1. Between 1,100 and 1,256 m, well Y-6 encountered suevitic breccias. In this well, the Chicxulub suevite appears to be stratified. The upper part of the Chicxulub suevite is composed of carbonate basement clasts and melt particles floating in a fine calcite, quartz, and feldspar matrix. Only a small fraction of the clasts are composed of target-rock anhydrite. The presence of carbonate melt and the scarcity of evaporite clasts must be taken into account when estimating the amount of CO_2 and SO_x vaporized. Below 1,253 m the proportion of silicate melt and basement fragments increases strongly, and the amount of carbonate decreases. Many of the quartz grains are recrystallized; others show planar deformation features or mosaicism indicative of shock metamorphism.

The need for drilling and coring within the deeper part of the impact basin, where the crater floor is buried under several hundred meters of Tertiary carbonate sediments, was recognized during the early studies of the crater because only the uppermost crater-related deposits were drilled early on (e.g., Urrutia-Fucugauchi et al. 1996). With the start of the International Continental Scientific Drilling Program, interest in drilling this crater in particular increased. The CSDP (Chicxulub Scientific Drilling Project) was formed as part of an international collaboration within the framework of

ICDP. In preparation for the ICDP drilling the National University of Mexico (UNAM) drilled several shallow holes near the rim of the crater (Urrutia-Fucugauchi et al. 1996).

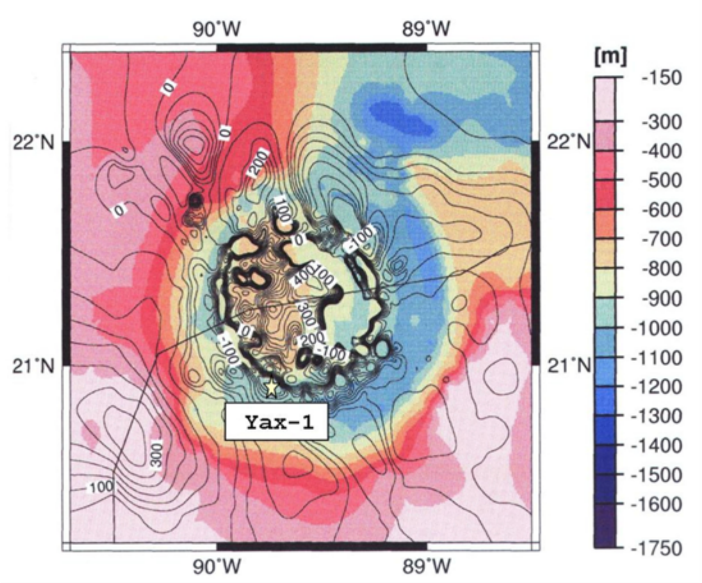

Fig. 5. Reconstruction of paleo-topography of the Chicxulub crater by subtracting the thickness of the Tertiary post-impact sediments based on seismic, gravity and borehole data (modified after Ebbing et al. 2001). ICDP borehole Yax-1 is located outside the central magnetic anomalies.

The most recent drilling project at Chicxulub was financed by ICDP and UNAM and was coordinated by UNAM (Urrutia-Fucugauchi et al. 2004). The CSDP borehole Yaxcopoil-1 was drilled from December 2001 through March 2002 in the southern sector of the crater. This spot is located about 62 km from the approximate crater center, just off the characteristic high-amplitude magnetic anomalies observed across the central uplift as defined by gravity and seismic data (Fig. 5). The Yaxcopoil-1 (Yax-1) borehole was planned to core continuously into the lower part of the post-impact carbonate sequence, the impact breccias, and the displaced Cretaceous rocks. The drill site at Hacienda Yaxcopoil was selected for a variety of logistical reasons that included site conditions and access, land ownership, water availability, and an environmental impact assessment (Urrutia-Fucugauchi et al. 2004). Yaxcopoil-1 (Yax-1) drilling extended to a depth of 1,510 m. Approximately 795 m of post-impact Tertiary carbonate rocks, 100 m of impactites, and 615 m of pre-impact Cretaceous rocks (megablock) were intercepted. The Tertiary rocks are composed of interlayered carbonaceous siltstones, calcarenite, and rare conglomerate and turbidite. The impactites are composed of suevitic and impact melt breccias that have both undergone significant alteration. These impact breccias have been subdivided into 5 units based on macro- and microscopic observations (e.g., Tuchscherer et al. 2004a, b)

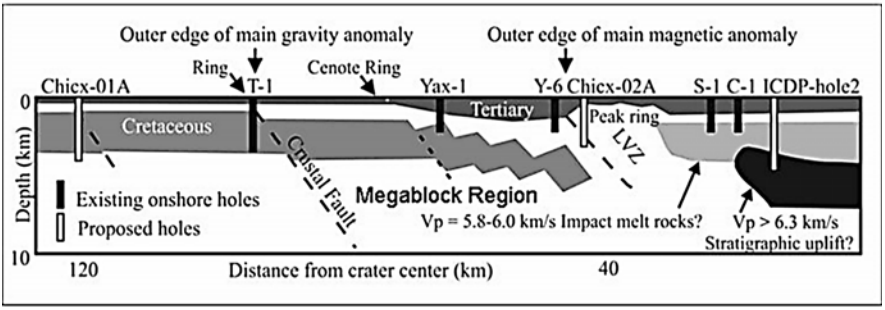

Fig. 6. Sketch of the multi-ring Chicxulub crustal structure with existing and proposed boreholes based on results from the new ICDP Yax-1 borehole and offshore-onshore seismic data (modified after Morgan et al. 2005).

Integration of the Yax-1 drill results with the existing geophysical and borehole database, including new offshore marine seismic data, led to a revised crustal model for the multi-ring Chicxulub structure (Morgan et al 2005). Despite not having reached the intended depth of well over 2 km, and the thinner than expected layer of suevitic breccias (thought to be the result of siting the drill site on a megablock (Fig. 6) that has moved in from the crater rim), many important studies have been completed on the core material, and extensive scientific results were gained. The main results were published in two special issues of the journal *Meteoritics and Planetary Science* in June and July 2004. However, given the size of Chicxulub, many questions remain open and additional questions came up as a result of the Yax-1 core results, making Chicxulub an ideal candidate for further drilling studies (see below).

5.2 Bosumtwi (Ghana)

This description of the Bosumtwi impact structure follows Koeberl and Reimold (2005). The crater is located in the Ashanti Province of southern Ghana, West Africa. It is situated near the regional capital town of Kumasi, which is also the second largest city in Ghana, as well as the capital of the Ashanti Kingdom. The Bosumtwi structure is centered at 06°32'N

Fig. 7. Panoramic image of Bosumtwi crater, looking south (photo by C. Koeberl)

and 01°25'W. It is one of only 19 confirmed impact structures known in Africa, and is the youngest well-preserved complex impact crater known on Earth. The structure, which has an age of 1.07 million years, is almost completely filled by Lake Bosumtwi of roughly 8.5 km diameter, and has a rim-to-rim diameter of about 10.5 km (Fig. 7). The crater has an outer ring structure (Fig. 8) of about 18-20 km in diameter, the origin of which is not well understood.

Since the 1930s, the origin of the Bosumtwi crater structure has been debated between geologists and geographers, who either favored an origin by volcanism or, only rarely, by meteorite impact. Only in the 1960s did this second hypothesis take hold, in particular because of the recognition that Bosumtwi could be the source crater for the Ivory Coast tektites. Ivory Coast tektites were first reported in 1934 from a rather geographically restricted area in the Ivory Coast (Côte d'Ivoire), West Africa. Later, microtektites were found in deep-sea sediments of corresponding age in the eastern equatorial Atlantic Ocean off western Africa. Ivory Coast tektites, related deep-sea microtektites, and the Bosumtwi crater all have the same age; close similarities between the isotopic and chemical compositions of the tektites and crater rocks show that Bosumtwi is the crater of origin for these tektites.

Lake Bosumtwi is a closed-basin lake with a detailed paleo-environmental record. The lake is at an ideal geographical location to provide an archive on climate variations with time scales ranging from seasonal to very long-term (Milankovitch cycle) for the West African monsoon and Sahel drought activity. Lake Bosumtwi has accumulated a detailed record of varved lake sediments that can be used to monitor both past local and Sahel rainfall variations. Rainfall over much of sub-Saharan Africa was highly correlated on centennial and longer time scales. Since the 1970s, a complex record of changes in lake level, lake chemistry, climate, and vegetation history has been documented by shallow piston core studies. Recent work has confirmed the research potential of such paleo-climatic studies (see, e.g., Talbot and Johannessen 1992; Peck et al. 2004).

Petrographic and geochemical work during the past 10 years has confirmed the presence of shock metamorphic effects and the presence of a meteoritic component in the Ivory Coast tektites as well as the breccias at the crater. Insights into the deep structure of the crater and the distribution and nature of ejected material and post-impact sediments were obtained by geophysical work started in 1998, which included aeromagnetic and airborne radiometric mapping, multi-channel seismic reflection and refraction profiles, and land- and barge-based gravity and magnetic studies. The seismic studies documented the existence of a central uplift underneath the lake sediments.

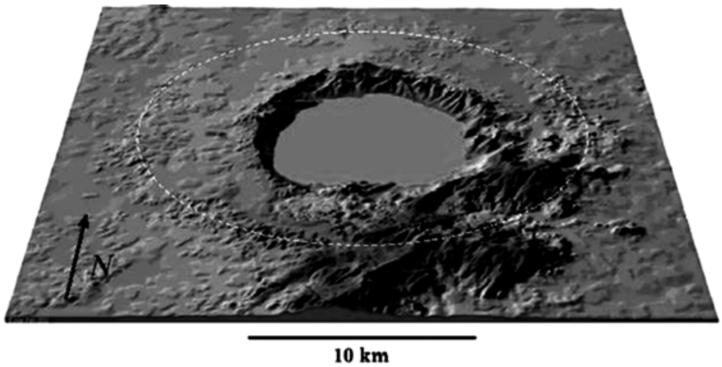

Fig. 8. Digital elevation model for the Bosumtwi impact structure (modified after Scholz et al. 2002). The outer ridge (dashed line) coincides with prominent radiometric anomalies (Koeberl and Reimold 2005).

All these recent studies led to the realization that further investigation of the crater still had the potential to provide additional important information, but that this could only be obtained from comprehensive, deep drilling of the crater. Planning for such a drilling project started in 2000, and in January 2001 a proposal was submitted to the International Continental Scientific Drilling Program (ICDP) to hold an international workshop in Potsdam in September 2001, which was intended to bring the various research communities interested in Bosumtwi (i.e., impact research, geophysics, paleo-environmental research) together. The workshop resulted in the definition of the goals for a deep-drilling project. There are several reasons for deep drilling from each of the two main driving research topics, but the two most important goals can be summarized as: (1) to obtain a complete 1-million year paleo-environmental record in an area for which so far only limited data exist; (2) to study the subsurface structure and crater fill of one of the best preserved, large and young impact structures.

More specifically, in terms of paleo-environmental studies, a deep-drilling project at Bosumtwi would provide information on: (1) long- and short-term changes in the West African monsoon; 2) hydrologic variation of the Sahel region; (3) dust export from various African Deserts to West Africa; and (4) sea-surface temperature variations in the tropical East Atlantic. Understanding the full range of climate variability in this region over the last 1 Ma will fill a major gap in our understanding of global climate dynamics, and thus lead to an enhanced climate prediction capability over a broad part of the Earth.

In terms of cratering studies, Bosumtwi is one of only two known young craters of this size (the other being El'gygytgyn in northeast Siberia), and may have a crucial diameter at the changeover between a traditional "complex" crater with a central peak and a crater structure that has a central peak-ring system. Drilling allows all the geophysical studies as well as material for geochemical and petrographic correlation studies between basement rocks and crater fill in comparison with tektites and ejected material.

As a result of the successful workshop in 2001, a full proposal was submitted to ICDP in January 2002. It was proposed to obtain drill cores at nine locations in the lake, with core lengths ranging from 50 to 1,035 meters. This would provide a total core length of 3 km of sediments and 1 km of impact-related rocks. The proposal was accepted by ICDP in mid-2002 and logistical work to organize and plan the drilling started in late 2002. Additional funding from various other national funding agencies in the United States, Austria, and Canada was obtained as well. A variety of permits had to be obtained, permission by government and tribal authorities had to be gained, and some construction work (such as road improvements and construction of a pier) was required. All this work was completed during early summer 2004. Drilling (Fig. 9) was then undertaken from the beginning of July to early October 2004 (see Koeberl et al. 2005, and Peck et al. 2005, for some first reports). Care was taken to situate all core locations on seismic lines that were measured in the preparation phase of the drilling project (Karp et al. 2002; Scholz et al. 2002). Figure 10 shows the locations of the hard rock and sediment cores that were obtained in the summer of 2004. Drilling was performed using the DOSECC/ICDP GLAD800 lake drilling system, which is a custom-built device specifically for lake scientific drilling. Funding for about 2/3 of the total cost was provided by ICDP.

Fig. 9. GLAD800 drill rig on Lake Bosumtwi in 2004 (photo by C. Koeberl).

In order to gain greater insight into the role of the tropics in triggering, intensifying, and propagating climate changes, scientific drilling for the recovery of long sediment records from Lake Bosumtwi was undertaken. Five drill sites were chosen along a water-depth transect in order to facilitate the reconstruction of the lake level history. At these five sites, a total of 14 separate holes were drilled. Total sediment recovery was 1,833 m. For the first time the GLAD800 lake drilling system (a system specifically constructed for drilling of lakes, for details see www.dosecc.org) cored an entire lacustrine sediment fill from lake floor to bedrock. The complete ca. 1 Ma lacustrine sediment fill was recovered from the crater ending in a narrow, possibly impact-glass (accretionary lapilli-like particle) bearing layer. This accretionary lapilli unit likely represents the initial post-impact sedimentation and provides an important age constraint for the overlying sedimentary sequence. The initial lacustrine sediment (located immediately above the impactites) is characterized by a bioturbated, light-gray mud with abundant gastropod shells suggesting that a shallow-water oxic lake environment was established in the crater. Future study of the earliest lacustrine sediment will address important questions related to the formation of the lake and the establishment of biologic communities following the impact. Most of the overlying 294 m of mud is laminated; thus, these sediment cores will provide a unique 1 million year record of tropical climate change in continental Africa at extremely high resolution.

Two additional deep boreholes (LB07A and LB08A) were obtained specifically for impact studies and their location was tied directly to detailed investigations of the potential field anomalies and seismic substructure that define the Lake Bosumtwi impact structure. Acquisition of zero-offset and multi-offset VSP (Vertical Seismic Profiling) data in deep hard-rock holes LB07A and LB08A established a link with existing seismic data. Downhole geophysical logging studies were conducted by the ICDP Operational Support Group to establish the necessary link between drill results from both the sediment and hard-rock drilling campaigns (Fig. 11). Slim-hole borehole geophysical studies (Fig. 11) provided crucial information about the distribution of magnetized formations within the crater fill and could potentially help locate discontinuous melt units in the proximity of the scientific drill hole(s). Information about the distribution of magnetic susceptibility and remanence of breccias and possible impact melt units held the key to an improved three-dimensional model for the Bosumtwi crater and its thermal history.

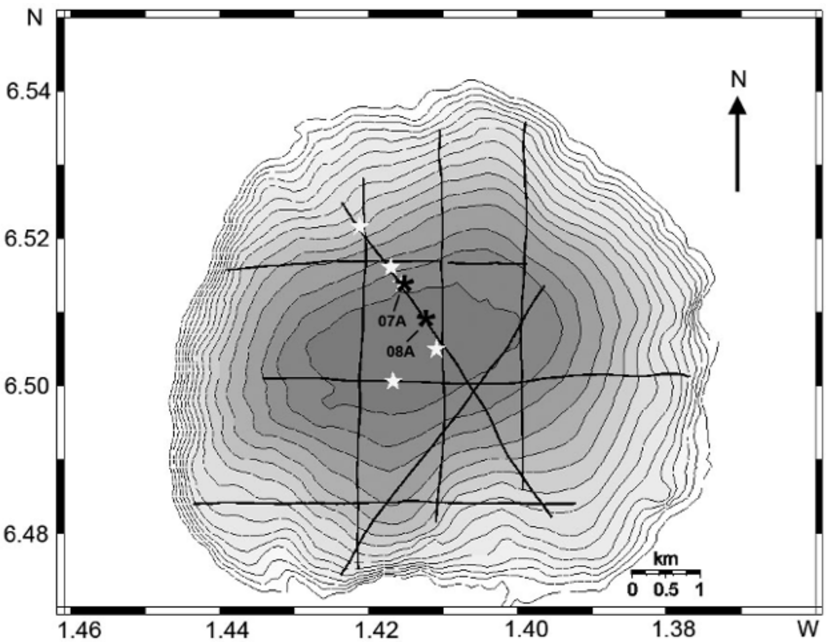

Fig. 10. Location of drill cores, water depth and seismic profiles in the Lake Bosumtwi structure. Gray stars, sediment cores; labelled asterisks: hardrock cores LB-07A and LB-08A (after Koeberl and Reimold 2005).

The hard-rock drilling phase, as well as borehole logging and geophysical studies, was completed on 2 October 2004. During that phase, two boreholes, to depths of 540 and 450 m, respectively, were drilled in the deep crater moat, and on the outer flank of the central uplift. In both cases, casing was set through the lake sediment part of the section, and drilling, using diamond coring tools, started at the sediment/impactite (i.e., post-impact sediment/fallback suevite) interface. Drilling progressed in both cases through the impact breccia layer into fractured bedrock. Figure 12 shows a few images of the cores retrieved from the crater fill breccia. After completion of the drilling and logging operations, the hard-rock cores (total of 122 core boxes) were shipped to the GeoForschungsZentrum Potsdam, Germany, for scanning and documentation. A sampling party took place in January 2005; samples were distributed in February 2005. First research results were presented at a special session at the 37th Lunar and Planetary Science Conference in Houston (USA) in March of 2006 (see, e.g., Koeberl et al. 2006).

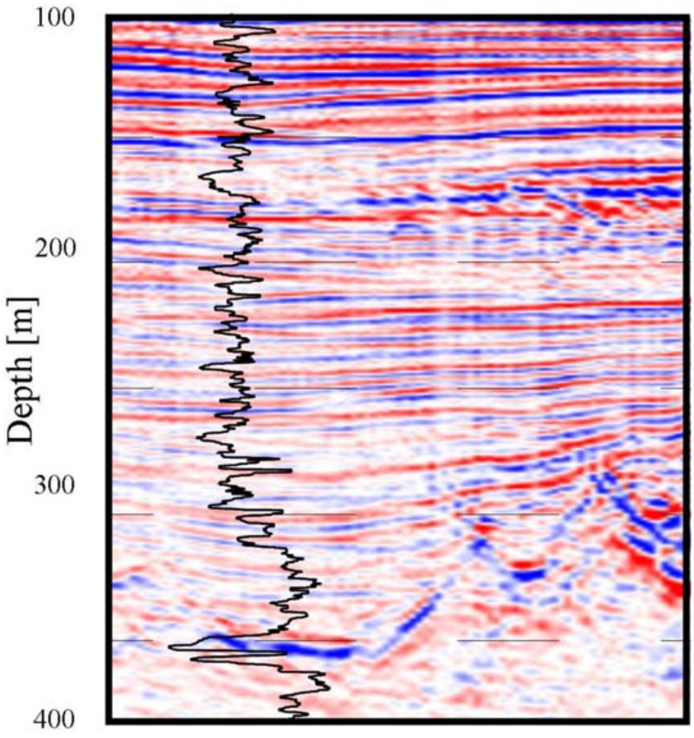

Fig. 11. Downhole geophysical logs establish a critical link between results from sediment and hardrock drilling at lake Bosumtwi. Dark line shows the gamma log obtained through cased borehole LB07A. Note impactites at 350 m depth.

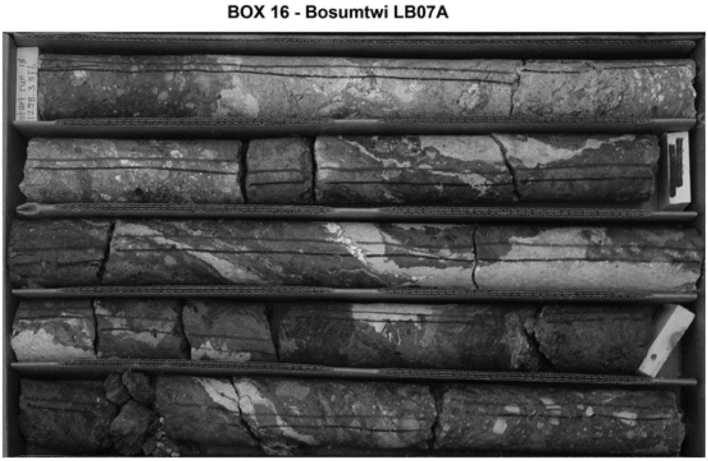

Fig. 12. Core box number 16 from corehole LB07A at Lake Bosumtwi, starting (upper left) at 383.5 m below lake surface, showing crater-fill breccia, a polymict impact breccia with some recrystallized melt (photo by C. Koeberl).

5.3 Chesapeake Bay (USA)

From September to December 2005, ICDP in conjunction with the United States Geological Survey drilled a deep borehole, which had a target depth of 2.2 km, into the Chesapeake Bay impact structure, Virginia, USA (Fig. 13). Chesapeake Bay, at ca. 85-90 km diameter (Poag et al. 2004), is among the Earth's largest and, at 35 Ma age, one of the best preserved impact structures known on Earth. It was formed within a 3-layer target, crystalline basement overlain by a well stratified sedimentary cover sequence, in turn below a shallow ocean of ca. 200 m water depth. Thus, the target sequence is very similar to that of the Chicxulub impact, although the water depth for Chesapeake Bay crater was much larger.

The Chesapeake Bay structure is of interest for a number of geo-disciplines. Its location on a passive continental margin has prevented post-impact tectonic disturbance. Marine deposition resumed immediately after the impact, leading to rapid burial of the impact formations and thus, good preservation. The upper part of the within-crater breccia lens has been extensively reworked by immediately post-impact environmental forces, including high-energy currents and possibly tsunami. Drilling was done into the crater moat, but close to the central uplift, to obtain as thick and as undisturbed a post-impact sequence of impactites and post-impact sediment as possible. The goal was to reach the crater floor, mainly in order to study shock barometry, hydrothermal effects below the crater, and possible breccia injections/in situ brecciation.

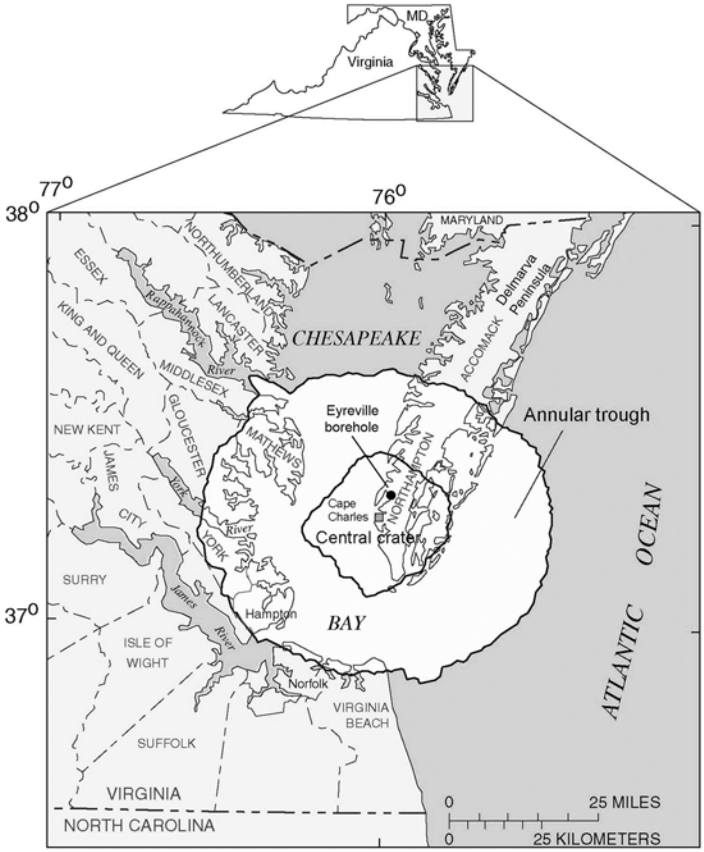

Fig. 13. Drilling location for the deep ICDP-USGS core hole near Cape Charles at the Chesapeake Bay impact structure, USA (after Poag et al. 2004).

The purpose of the ICDP-USGS drilling project was fourfold:

1. Impact studies, with regard to the impact into a “wet” target. In contrast to impacts into “dry” targets, the uppermost ocean target layer affected crater excavation, collapse, and late-stage infilling, and overall, the final crater geometry. At present, there is no comprehensive data set from a terrestrial impact crater that allows us to test the results of numerical modeling of such an impact event. Basic parameters of the Chesapeake Bay impact crater, even the actual diameter of the structure, are still controversial and require firm constraints. The drill core obtained will

provide extensive information regarding this cratering process, in comparison with knowledge from other impact structures, especially Chicxulub. In addition, the in-crater impact deposits will allow an investigation into the original target composition as well as that of the impactor. The possible presence of an impact-activated hydrothermal system, with possible implications for ore genesis, is of great interest to impact workers and economic geologists alike. The Chesapeake Bay impact has been related to the North American tektite strewn field, but the proposed connection is still tentative and requires further firm constraints.

2. Post-impact studies involve the documentation of the impact-triggered local biotic crisis, recovery of the bio-system, and study of impact-related environmental effects on sea-level, climate and sedimentation in the short- and long-term evolution of the mid-Atlantic continental margin. This program provided the opportunity to compare a continuous sedimentary profile through post-impact sediment in the crater area with the well-constrained upper crustal sections already on hand for the region covering northern Virginia to New Jersey. This elucidated the long-term effects of a major impact event on a trailing continental margin by comparison with the "normal" tectonic and sea-level history of that margin.
3. Detailed hydrogeologic investigations of the brines in the cored sediment section were carried out, including salinity and other chemical and physical parameters of groundwater, as well as groundwater/seawater exchange. This will elucidate the hydrogeologic history of the Chesapeake region as well as provide valuable data for improved modeling of the current freshwater reservoir in this densely populated region. The impact structure coincides with a well-known but poorly modeled "saltwater wedge" within the Virginia Coastal Plain, which is a serious threat to the fresh-water supply of at least 2 million people (Poag et al. 2004).
4. Astrobiology and deep biosphere issues. The deep drill core provides an opportunity to study microbial communities at significant depth in the Earth's crust.

In 2003, the Chesapeake Bay Impact Crater Deep Drilling Project began with an international workshop, followed by a full proposal sent to the ICDP in January 2004. The proposal was approved during 2004 and drill-site activities began with extensive site preparations during July 2005. The drill rig arrived in early September, and the first core sample was recovered on 15 September 2005. The drill site was located on private land at Eyreville Farm, which is located between Cheriton and Eastville on Virginia's Eastern Shore (Fig. 14). The project ran into various unexpected difficulties, when parts of the first core hole had to be abandoned because the drill string became stuck in the well, a likely result of swelling clays. This led to loss of almost 2 weeks of coring time and also to the loss of parts of the drill string. Both losses caused an unexpected and serious financial setback. In addition, underneath the sediment-clast dominated breccia, the drilling encountered a ca. 270-m-thick granite block, which slowed down drilling by at least a factor of two compared to coring in "normal" impact breccia. These problems would have led to a projected shutdown in mid-November 2005 due to exhaustion of the original funding. Stopping the drilling at that time would have caused a loss of major scientific return of the project. Fortunately, it was possible to secure emergency funding from ICDP, NASA, and USGS, allowing further drilling until the project successfully completed its scientific drilling operations on 4 December 2005, when the drill bit reached a final depth of 5,795 feet (1.77 kilometers). One of the important lessons from these project phases was to recognize the importance and short-term availability of contingency funding.

Fig. 14. ICDP-USGS drill site at Eyreville Farm near Cape Charles, Chesapeake Bay impact structure, October 2005 (photo by C. Koeberl).

A sampling party was held at the US Geological Survey in Reston, USA, from March 198-21, 2006. A summary of the drilling operations, and some first results, were summarized by Gohn et al. (2006a, b).

5.4 El’gygytgyn Impact Structure

The El'gygytgyn impact structure is located in the far northeastern part of Russia (centered at 67° 30’ N and 172° 05’ E) in the Upper Mesozoic Ochotsk-Chukotsky Volcanic Belt of Northeast Asia. The structure, which has an age of 3.58 Ma, was originally described as of volcanic origin. However, from the late 1970s onwards some evidence for an impact origin was discovered. The crater forms a flat-floored circular basin with a rim-to-rim diameter of about 18 km (Fig. 15). The crater is one of the best-preserved impact structures on Earth with excellent morphological expression. The crater floor, about 14 km in diameter, is largely covered by the nearly circular El’gygytgyn Lake, which is 12 km in diameter and up to 170 m deep in its central part. This lake is somewhat offset from the structure’s center as ascertained by the crater rim. A complex system of lacustrine terraces surrounds the lake. A central peak is not exposed on the surface of the crater floor, nor is it evident in bathymetric data of the lake bottom. However, gravity measurements from the 1980s suggested the presence of a ~2 km wide central peak underneath post-crater sediments, and centered relative to the crater outline. Nolan et al. (2003) suggested that the central uplift is centered within the outline of the lake, which, however, would offset the central uplift relative to the crater center. In contrast, recent seismic work cited by Melles et al. (2003) seems to confirm that the central uplift is centered relative to the crater rim, not the lake.

El’gygytgyn represents the only currently known terrestrial impact structure formed exclusively in siliceous volcanics, including tuffs. The impact melt rocks and target rocks provide an excellent opportunity to study shock metamorphism of volcanic rocks. The shock-induced changes observed in porphyritic volcanic rocks from El’gygytgyn can be applied to a general classification of shock metamorphism of siliceous volcanic rocks (cf. Gurov and Koeberl 2004). These authors found that strongly shocked volcanic rocks with phenocrysts converted to diaplectic quartz glass and partially melted feldspars as well as cryptocrystalline matrices are widespread in the El’gygytgyn crater. In particular, the following different stages of shock metamorphism are observed: (I) weakly to moderately shocked lavas and tuffs with phenocrysts and clasts of quartz and feldspars; (II) moderately shocked volcanic rocks and tuffs with diaplectic glasses of quartz and feldspars; (III) strongly shocked lavas and tuffs with phenocrysts of diaplectic quartz glass and fused glasses of feldspars in melted matrices, (IV) impact melt rocks and impact glasses. In recent years, the post-impact geological and climatic history of the area around El'gygytgyn crater and, especially, its sedimentary record have been extensively investigated in a joint research program of the Alfred-Wegener-

Institute, Bremerhaven (Germany), the University of Massachusetts, Amherst (USA), and the North-East Interdisciplinary Scientific Research Institute, Magadan, Russia (cf. Brigham-Grette 2002).

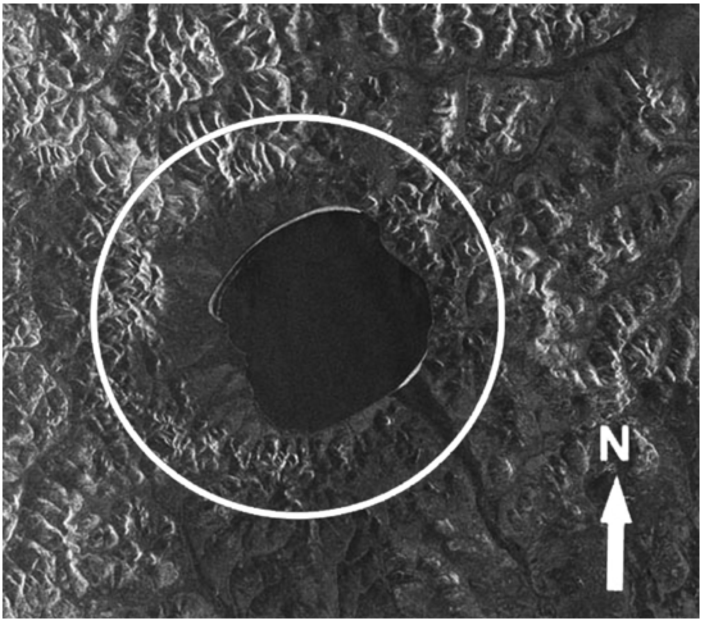

Fig. 15. Radar image of the El'gygytgyn impact crater, Russia. The lake, which is somewhat eccentric within the crater, has a diameter of about 12 km (e.g., Gurov and Koeberl 2004).

Lake El'gygytgyn is the only place in the terrestrial Arctic with a continuous 3.6-million year climate record, and such a record is required to fully understand the Arctic's role in global climate dynamics. Of primary interest to the scientific community is determining why and how the arctic climate system evolved from a warm forested ecosystem into a cold permafrost ecosystem between 2 and 3 million years ago. A continuous depositional record in a lake at this latitude provides a means of determining from a terrestrial perspective how the arctic climate evolved and subsequently evolved during Milankovitch-driven glacial/interglacial cycles (i.e., over 41 ka cycles and, later, over 100 ka cycles). Our present understanding of the lake as an ecosystem suggests we can interpret higher resolution climate change events across eastern Siberia on centennial to millennial scales and test for atmospheric connections with other long climate records worldwide. Such comparisons will offer insight into the dynamic mechanisms behind these connections or the lack thereof, and an understanding of the conditions for permafrost formation and stability through time, especially in the context of modern warming.

Because of the potential for unique paleoclimate and impact studies, following an earlier ICDP workshop in 2001 a full proposal for drilling was submitted to ICDP in January 2005 and the Lake El’gygytgyn project was subsequently funded. Coring objectives include replicate cores of 630 m length to retrieve a continuous paleo-climate record from the deepest part of the lake and underlying impact breccias and bedrock. Studies of the impact rocks offers the planetary community the opportunity to study a well preserved crater formed in the midst of igneous rocks, a crater situation not unlike some situations on Mars. One additional core to ca. 200 m into permafrost from the adjacent catchment area will allow us to test ideas about arctic permafrost history and sediment supply to the lake since the time of impact. Drilling is currently planned for the first four months of 2008.

6 Future Goals for Impact-Related Drilling

6.1 The Need and Relevance of Scientific Impact Crater Drilling

As mentioned above, impact cratering is one of the fundamental processes in the Solar System. It is certainly the most important surface-forming process (Melosh 1989). In addition, since 1980, it has been shown that an impact catastrophe has caused large-scale evolutionary change in life on Earth at least once during the Phanerozoic: namely, at the Cretaceous-Tertiary (K-T) boundary, when the impact event at Chicxulub caused a rapid decline of some 70% of all organisms living at the time. Whether or not impact events at other points in life’s geologic history played a similar role is widely debated in many sections of the geoscientific community. Since the 1980s, recognition of impact as an enormously important geological process and its role in evolution have revolutionized geoscience, a phenomenon similar to the earlier revolution in thinking brought on by the acceptance of plate tectonics. Impact crater drilling has vast potential to contribute to the general understanding of the impact process and its related energy distribution. It will allow for the investigation of first-order impact-related questions but also post-impact geological and environmental effects, including destruction of life and re-establishment of life in the impact-affected region.

At the present time, the only available source of three-dimensional information on the lithological and structural character of impact structures is from direct observations at terrestrial impact structures. Such information is available only through field studies at impact structures, which may be eroded to differing depths depending upon the circumstances, through geophysical studies, and/or via drilling. Although potential field data are the most widely available geophysical data, they are generally insufficient to provide unequivocal or detailed interpretations of the subsurface character of impact structures. Reflection seismic data has the potential definition and resolution to significantly enhance structural and/or lithological interpretations, but such interpretations are only unique when complemented by ground truth data obtained through drilling. For example, while reflection seismic data have resolved a peak ring at the 180-km diameter Chicxulub structure, in the absence of direct sampling, the lithological and structural character of this ring is unknown and controversial (Morgan et al. 2002).

6.2 Some Specific Issues that Require Drilling

Previous impact-crater drilling was largely focused on the identification of a particular structure as having an impact origin or on basic characterization, with the exception of a few more recent drilling projects and corporate drillings, which by their nature address economic, not scientific, questions. Here, we consider some impact-related scientific questions that could be addressed through future focused drilling at terrestrial impact structures (Table 1). They are in no particular order, with respect to priorities. They also do not consider the use of impact craters for other types of studies, e.g., climate change or paleo-climate studies. As isolated, and sometimes singular, basins, impact craters are ideal sites for the accumulation of sediments. For example, the New Quebec crater (Canada) most likely contains a complete and undisturbed record of the climate since Laurentide deglaciation in the eastern Arctic of North America.

6.2.1 Transient Cavity Geometry at Simple Craters

Given its importance, it is surprising that the working hypothesis for the transient cavity and its collapse at simple impact structures has received little scrutiny. A geometric model for wall slumping was developed and combined with a Z-model to simulate excavation and displacement within the transient cavity (Grieve and Garvin 1984). The analytical model was tested using drilling data from Barringer, Brent, Lonar, and West Hawk craters and 3-D interpretations based on gravity models at Aouelloul, Tenoumer and Wolfe Creek structures (Grieve et al. 1989). Although information from drilling is available from other structures, notably in the former USSR (e.g., Masaitis et al. 1980), textual or tabular information, as opposed to graphical information, on dimensions are generally not available. Thus, testing the validity of the concept of transient cavity wall collapse at simple craters is based on data and interpretations at only seven simple impact structures and three of these are non-unique interpretations of depths from gravity data.

6.2.2 Structural Uplift and Shock Zonation at Complex Impact Craters

Hydrocode models of transient cavity collapse in the formation of complex impact structures require that target-rock strength be reduced (e.g., Melosh and Ivanov 1999). Suggested mechanisms include acoustic fluidization (Melosh 1979) and weakening of the target rocks by shock heating (O'Keefe and Ahrens 1993). Drill cores at terrestrial complex impact structures in sedimentary targets indicate thrusting and faulting in the structural uplift (e.g., Brenan et al. 1975; Offield and Pohn 1977) indicative of the target material behaving as blocks, at least during structural uplift. Reflection seismic data over structural uplifts indicate a loss of coherent reflections and a reduction in seismic velocity (e.g., Scott and Hajnal 1988; Milton et al. 1996). This is attributed to the occurrence of discrete blocks in the structural uplift.

The perception that the structural uplift behaved as some form of relatively coherent mass or series of large blocks comes mostly from terrestrial complex impact structures in crystalline targets; particularly from less eroded examples with relatively poor rock exposure over the structural uplift (e.g., Manicouagan). Lithological markers in such rocks, which could help establish the degree, location and nature of deformation, are generally absent. At more eroded structures, where the structural uplift is better observed, and in areas of good exposure (e.g., the coastline of Slate Islands), breccia dikes separating discrete blocks are ubiquitous in the structural uplift (Grieve and Robertson 1976; Dressler et al. 1998). Similarly, in drill cores, where sampling of the structural uplift is (close to) 100%, blocks in the tens to hundreds of meters size-range are apparent, for example at Puchezh-Katunki (Ivanov et al. 1996) and the Manicouagan and West Clearwater, Canada, structures (Geological Survey of Canada, unpublished data). However, none of these previous studies were designed specifically to address the three-dimensional geometry of shock wave attenuation rates at complex impact craters and none have effectively tested the mechanism(s) for reducing target rock strength during uplift.

Clarification of the three-dimensional end-state of shock zonation at complex impact structures and comparisons with the modeled zonation during the initial stages of impact at transient cavity formation, would provide important constraints on the nature and trajectories of uplift motions during cavity modification.

6.2.3 The Nature of Ring Structures

Impact basins are defined as a crater form with one or more topographic ring structures interior to the rim (Spudis 1993). This definition is relatively straightforward in terms of its application on the moon (albeit it becomes more interpretative for the oldest, heavily degraded basins). It has been, to say the least, highly interpretive in the terrestrial environment (e.g., Pike 1985). However, the largest known terrestrial impact structures (Chicxulub, Sudbury, and Vredefort) display some observational evidence of ring forms, but the genetic relationship and equivalence to what is observed at impact basins on the moon is not clear. At Chicxulub, interpretations of offshore reflection seismic data indicate a topographic peak ring (Morgan et al. 2002). At Sudbury, there are claims of rings of increased pseudotachylite development, which have been equated with the traces of super-faults related to rim collapse and modification (Spray et al. 2004). At Vredefort, there are a series of concentric anticlines and synclines, reflecting thrust structures in the sub-floor of the impact structure (e.g., Brink et al. 1997).

Lunar observations indicate that the exposed volume of central peaks increases with rim diameter. There is, however, a change in the amount of relative increase in volume above rim diameters of ~ 80 km, corresponding to a reduction in the rate of increase in the relative height of the central peak, which reaches a maximum of ~ 2 km (Pike 1977; Hale and Grieve 1982). This reduction in the rate of increase of central peak volumes coincides with the appearance of rings of high-amplitude floor roughening between the central peak and the rim. This is generally consistent with ring formation being an extension of the process of structural uplift in complex impact structures, with the dynamic collapse of an initially overheightened central peak and the accommodation of the volume of uplifted material, being manifested as rings (Melosh 1989).

Some terrestrial observational data also favor an extension of the structural uplift processes in the formation of rings. Assuming that Sudbury and Vredefort had the original form of impact basins, they display the sequence of a central structural uplift with lithologies progressively becoming younger outwards and representing successively nearer surface lithologies in the original target. Post-impact tectonic movements at Sudbury, particularly in the south, have complicated the expression of the structural uplift at Sudbury and a large portion of the structure has been tectonically deformed. The structural relations at Vredefort are less complicated but, like Sudbury, are reflections of not only impact processes but of pre- and post-impact tectonic processes (Henkel and Reimold 1998).

Recent hydrocode models (Collins et al. 2002; Ivanov and Artemieva 2002) indicate that an over-heightened central peak and its outward collapse form a ring through interference with the inwardly collapsing transient cavity wall. In this case, the models have achieved such a degree of sophistication with respect to large-scale natural impact events that they have a degree of predictability that can be tested. Given the level of erosion, such a test would be limited to Chicxulub. According to the models, the peak ring at Chicxulub would display inverted stratigraphy. Given that Chicxulub is buried by ~ 1 km of post-impact sediments, such a test can only be administered through drilling. The geographical location of the topographic peak ring has only been determined with a degree of certainty by interpretations of reflection seismic profiles offshore in the Gulf of Mexico (Morgan et al. 2002). It would, therefore, seem that the ground-truth information on the formation of rings in terrestrial impact basins depends critically upon such enterprises as the Integrated Ocean Drilling Program (IODP) and cooperation with ICDP.

6.2.4 Testing Impact Physics Models

Even for a vertical impact with a given projectile size and velocity, the final crater shape may be different for different rheological models or for different input parameters within a single model (e.g., see Artemieva et al. 2004). Figure 16 shows the final crater morphology and density distribution for simulations where the only parameters varied were the coefficient of friction for the damaged rock material and the decay time of the acoustic pressure vibrations (which are assumed to fall in amplitude exponentially with time). The run without any target softening (that is, where the effects of acoustic fluidization were not considered) produced a 10-km-diameter, deep crater with only partially collapsed rim walls (A-plate in Figure 16).

It is important to compare the model predictions with available observational data. Results of numerical simulations span a range of impact parameters (projectile size and velocity, impact angle, target strength parameters). Numerical studies provide important predictions for the physical properties of the rocks under the crater floor, which may be evaluated by scientific drilling: the value of maximum shock compression may be directly connected with shock metamorphic features in the target rocks; the presence of the projectile material may be confirmed by geochemical analysis of brecciated materials and melts; the temperature distribution constrains the region of natural remanent magnetization and, in combination with predicted fracture distribution, defines the zone of intensive post-impact hydrothermal activity. In the future, the interpretation of geophysical, geological and petrophysical data will allow us to compare the numerical results with gravity (combination of target deformation, fracturing, shock metamorphism) and magnetic (combination of melt, demagnetization, chemical changes) anomalies. This will provide further validation of the numerical model itself and powerful insight into the impact cratering process.

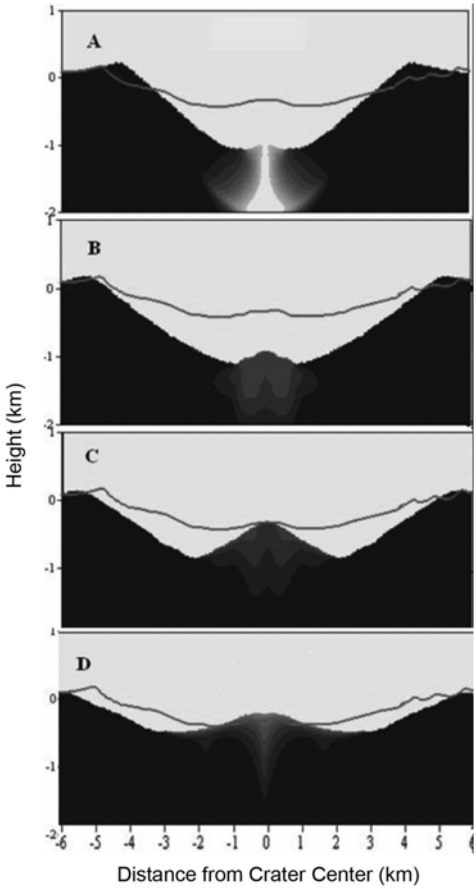

Fig. 16. Comparison of the impact modeling results with seismic and topographic data (red line) for the Lake Bosumtwi crater. A: acoustic fluidization, simple crater. B, C, and D: acoustic fluidization model with increasing decay times modified (after Artemieva et al. 2004).

6.3 Other Considerations

The value of observations at terrestrial impact structures for understanding impact processes is clear; interpretations of these observations have resulted in an evolution in the understanding of crater processes and will continue to do so in the future. There is also considerable potential value in re-examining existing materials and observations at terrestrial impact craters with newer methodologies and technologies. For example, the polymict breccia sheet that is contained within the Haughton structure was recognized as the spatial equivalent of coherent impact melt sheets observed at other terrestrial complex impact structures in crystalline targets (Grieve 1988). Its origin, however, was considered analogous to a suevite deposit, with a clastic matrix (Redeker and Stöffler 1988). More recent examination of the matrix at the scale of the SEM, indicates that the matrix contains both Si-Al-Mg-rich glass and microcrystalline carbonate, containing a few weight percent Si and Al. Globular textures of calcite within the silicate glass and quench crystals of pyroxenes point to the matrix phases being originally molten and rapidly cooled (Osinski and Spray 2001).

These new observations indicate that the breccia deposit is not only the spatial equivalent but is also the genetic equivalent of the coherent melt sheets found at complex impact structures in crystalline targets. This goes some way to removing the pre-existing inconsistency between theoretical considerations and analytical models that indicated that sediments underwent impact melting at shock pressures equivalent to or lower than crystalline rocks but that coherent impact melt rocks of sedimentary origin were apparently absent in the observed record, being replaced by "suevite" breccia (Kieffer and Simonds 1980).

There is a renewed interest in impact structures in sedimentary basins and associated hydrocarbon reservoirs, although this research activity is a bit off the screen as access to 3D-seismic data, borehole logs and drill core data are governed by tight confidentiality agreements. Nevertheless, information about enhanced porosity and permeability in breccia and footwall rocks from current ICDP projects (Chicxulub, Chesapeake Bay, and Bosumtwi) will be an important contribution for this new research direction.

Clearly, our understanding of the large (Sudbury) and poorly exposed craters (Mjølnir) would greatly benefit from deep-drilling efforts. This being said, the scientific return of future ICDP projects will be enhanced by the integration of secondary targets: the deep biosphere; monitoring of stress; fluids and gases in new deep boreholes; and permanent installation of sensors. The challenge is to fully integrate these secondary targets in the scientific proposals, the project's financial budget and the management plan.

Generally speaking, deep scientific drilling projects should have a well defined set of deliverable items, among them should be a calibrated 3D-Earth model for the study site. Important reasons for drilling into impact craters include: a) impact craters are unique in terms of geological processes (the only geological process with a known start time); and b) craters are the largest sediment/dust traps on Earth.

Impact-related drillings do not only yield scientific data for the impact community, but for the general scientific community as well. The successfully drilled bore holes can be preserved by extra casings and proper shielding. Such deep holes can then act as permanent geo-laboratories allowing several scientific monitoring experiments to be carried out in future years. These may be related to monitoring fluid or gas motions in the hole, micro-seismics, temperature or pressure changes, slow developments of breakouts, biological monitoring (bacteria movements), etc. Moreover, the holes provide opportunities to test new geophysical logging instruments and to carry out international calibrations of geophysical techniques or to test new techniques or novel innovations in instrumentation.

The following list singles out a number of aspects of impact cratering and the geological record that can be investigated with impact crater drilling:

- Ground truth for confirmation of origin of structures (not without other objectives);
- Ground truth to complement numerical modeling (we have already learnt from the few previous drilling projects that we know very little about the interior of impact structures, i.e., the distribution of impactites, the types of impactites generated in different target environments, the geological structures of large, complex impact structures, distribution and dispersal of ejecta, distribution of meteoritic components, etc);
- Basic data for the modeling of environmental effects of large, catastrophic impact events; and
- Utilization of impact structures for paleo-climatic/environmental investigations – integral studies of the Global Change Program.

In favorable cases, drilling for the above reasons will have major benefits for society.

6.4 The Need for International and Multidisciplinary Cooperation

Impact research is internationally widespread, but typically comprises locally rather small research groups that commonly are interrelated in various international and national networks. In order to achieve large goals and fulfill projects of some size, international and interdisciplinary organizations are needed. This is important in particular for the confined scientific impact-community. In addition the impact processes, from the time of impact, via different phases of deformation, excavation and distribution of ejecta, do not follow political or national boundaries; international approaches are necessary to reach the best and most complete answers. An inclusion of the impact themes in the ICDP science plan has consequently both strong organizational and scientific arguments.

Impact crater drilling has significantly reinvigorated the activities of the impact-cratering community, and the resulting consortia have been the focus of enhanced interaction and collaboration of individual workers and working groups. The impact-cratering community has been revitalized, with a number of new workers having been attracted into the field through postgraduate and post-doctoral research programs as part of the ICDP drilling-based and multi-disciplinary research projects. Consequently, the understanding of the geology of large impact structures and the cratering-related processes has been improved.

Interdisciplinary collaboration has been fertilized with scientists from most diverse disciplines such as the life sciences and all parts of the geosciences participating in pre- and post-drilling workshops and symposia. Thus, ICDP drilling of impact structures has not only had a most beneficial return for the impact cratering community but for a much wider sector of the geo-community.

6.5 Lessons from Past Work

The past three ICDP-financed impact crater drilling projects have resulted not only in excellent scientific return, but also provided invaluable practical lessons. Some of these should be mentioned here to aid planners of future projects. For example, extrapolation of reflection seismic sections by several kilometers from the actual data line is dangerous. Drilling in “difficult countries” can severely stretch logistics and sap funds. Even selection of Principal Investigators (PIs), especially those from within the country where drilling is to take place, can become a serious issue.

The availability of emergency (contingency) funding has emerged as an important consideration. For example, if such funding would not have been secured (which was done with great trouble and under extreme time pressure) for the Chesapeake Bay crater drilling in November 2005, about half of the science return would not have been secured – even though the additional finances amounted to only about 10 percent of the already committed and spent funds. Small amounts of add-on funding, available in case of real need, should be part of any future ICDP funding strategy. Such funds could be obtained from unspent portions of other projects, or simply made part of the general financial considerations of ICDP. Another point concerns the establishment of a central data repository that would include data also from previous (non-ICDP) drillings. A lot could be learned from pooling such information.

6.6 Strategy for Defining New Drilling Sites within the ICDP

Future ICDP drillings of impact sites should focus on contributing to the solutions of some of the fundamental questions of impact cratering listed below (Table 1). The priority should not be to focus on one particular crater to understand its specific characteristics, but priority has to be given to achieving a better understanding of the processes which form the crater and which lead to regional and global geological, environmental, and biological effects. Finally, future scientific drilling projects must include and interpret all available geoscience data (from drill core to remote sensing).

Science targets at impact structures and considerations for the future are:

- 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 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 can 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.
- Determine the nature of a topographic peak ring.
- 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?
- Relation of melt volume and melt distribution to target rheology (porosity, sediments versus crystalline), impactor type, and velocity?

7 Specific Suggestions for Future Impact-related Drilling

ICDP drilling projects into large buried impact craters (such as Chicxulub and Chesapeake Bay) will be of crucial importance in solving not only the sizes/depths of impact effects and to provide materials for dating, but also to understand their effects on the biosphere. However, in most cases the verification of impact origin of the smaller impact craters relies almost uniquely on drillings. The small craters can be occupied at present by shallow seas (commonly bays), or lakes. These drillings, as the ICDP Bosumtwi and El'gygytgyn projects will reveal, provide two or more sets of useful data. The post impact sediments are well preserved and provide a unique record of climate and of the geomagnetic field since the impact. Second, the drillings can be performed so that the impact structure below the lake or sea can be penetrated deeply enough to yield samples of the impact layers through the fractured target rocks and down to the unshocked target rocks in a continuous sequence. The last point is important since theoretical arguments reveal that the shock should decay exponentially and radially away from the point of impact; only drilling can yield a continuous sequence of samples to see this decay of shock and thus yield the necessary constraints for impact modeling studies. The calibration of forward modeling studies is of fundamental importance to fully understand the impact cratering processes in terms of shock, temperature and rock properties.

Future impact related drilling projects should be interdisciplinary to, and continue to focus on world-class geological sites (e.g., Sudbury), enter collaboration with other international organizations (e.g., IOPD) to probe shallow water marine sites (Mjølnir), and revisit existing key reference sites (such as Chicxulub and the Ries) in order to build better three-dimensional models of impact craters. At the same time, impact-related scientific drilling should integrate as much as possible state-of-the-art research efforts into biological, paleo-climate, resource and socio-economic aspects of impact craters.

Table 1. Major open questions in impact cratering research

Crater morphology	Cratering mechanics	Global environmental effects	Regional large-scale geological effects
What factors are relevant for the size dependence of the transition from simple to complex craters with (a) central uplift, (b) peak ring, and (c) multiple rings?	What physical processes are responsible for the collapse of the transient cavity and for the formation of the various types of complex craters?	What is the role of crater size? What is the role of the composition of the target rocks?	What are the detailed time-dependent processes during the formation of large impact melt complexes and during their differentiation?
What is the role of the target rocks ranging from crystalline rocks to mixed targets and pure sedimentary rock strata?	What evidence can be found for the transient loss of strength of the crater material, e.g., the study of drill cores? Can models, e.g., “acoustic fluidization”, be verified?	What are the detailed chemical and physical processes during the interaction of vapor, melt and dust with the atmosphere?	What are the conditions and processes for the formation of sulfide ore deposits in large impact melt complexes?
What is the effect of water-bearing or volatile-rich rock types?	What is the time-dependent process in the formation of the ejecta plume and its collapse?	What are the short- and long-term global climatic effects?	What are the effects of post-impact hydrothermal activities and their time scales?
Why are the transition diameters and the morphologies different from planet to planet and what are the influencing parameters?	What factors are important for the global distribution of ejecta (vapor, melt, dust) and its interaction with the atmosphere?	What are the details of the cause-effect relationships for mass extinctions caused by impact?	What is the role of these processes in the early Archean (during the early heavy bombardment phase)?

7.1 Sudbury, Canada

The Sudbury Structure (Canada) offers the only example of a basin-sized (250 km diameter) impact structure on Earth (Fig. 17) 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 and has produced more than $100 billion worth of metal in over a century of production. Sudbury is the premier locality on Earth to study processes related to impact and planetary accretion, as well as a wide range of magmatic processes including the generation of large magmatic sulfide deposits through scientific drilling.

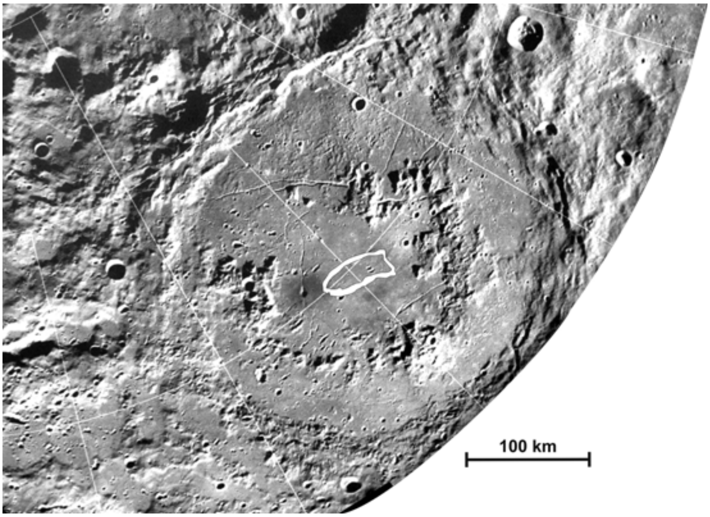

Fig. 17. Part of the surface of the Moon, showing the impact basin Schrödinger, 320 km in diameter. For comparison, one of the Earth's largest impact structures, the Sudbury Basin (Canada) is superimposed (white outline). The Sudbury Basin, which is 60 km long and 30 km wide, is estimated to be the deeply eroded remains of an originally 200 to 250-km-diameter, 1.86 Ga old, impact structure.

After impact, the entire 1.85-Ga Sudbury structure was affected by north-west directed thrust faulting, folding and associated lower amphibolite facies metamorphism. The Sudbury Structure is characterized by prominent potential field anomalies (Fig. 18).

The Sudbury Igneous Complex (SIC), the preserved portion of a silicate melt body several kilometers deep and more than 60 kilometers across, was produced virtually instantaneously by shock heating and cooled without further inputs of melt. The boundary conditions on this cooling and igneous differentiation process are simpler and can potentially be better understood than at any other large igneous body on Earth.

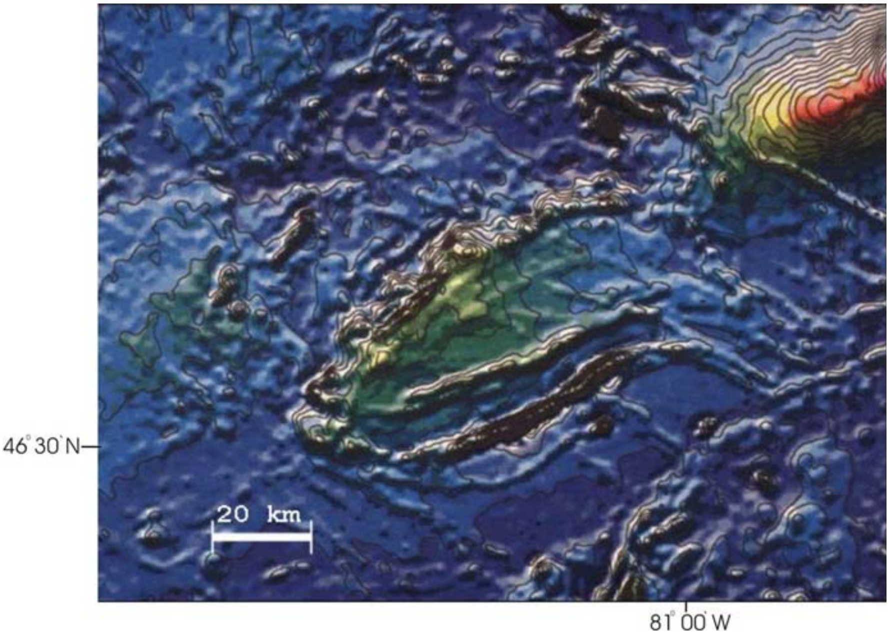

Fig. 18. Magnetic signature of the deeply eroded Sudbury structure (modified after Roest and Pilkington 1994).

Because the Sudbury Structure has been deformed since its formation, its large-scale subsurface geometry remains a matter of conjecture. Several seismic reflection and refraction transects and potential field studies were conducted across the Sudbury structure and provide a unique framework, when integrated with existing knowledge from mineral exploration, for 3D subsurface models. However, some of the deep crustal reflection images can be interpreted in a number of different ways that each honor the existing borehole, gravity and magnetic field data, as well as geological and structural constraints. Some data interpretations place potential hosts for important ore deposits close enough to surface to permit future exploitation, with obvious economic ramifications (Fig. 19). Future deep drilling at Sudbury will test competing 3-D subsurface models derived from the existing shallow borehole, geological, structural and geophysical data. In addition, any deep drilling project will make use of wire-line diamond drills with core diameters considerably smaller than drills used in the petroleum industry. The relatively light weight, low cost and the versatility of this slim-hole technology makes it the method of choice for the mineral exploration industry worldwide. In South Africa, this method was successfully employed to drill and core to 6 km depth.

Furthermore, the Sudbury Structure is also a unique example of a very large differentiated igneous body with remarkably simple boundary conditions. As such, it is the premier locality on Earth to study processes related to impact and planetary accretion, as well as a wide range of magmatic processes including the generation of large magmatic sulfide deposits. In terms of sustainable development, future (robotic) mining at depths considerably greater than are attained today requires reliable estimates of key geotechnical parameters (such as in situ stress and temperature), something that can only be achieved through deep scientific drilling.

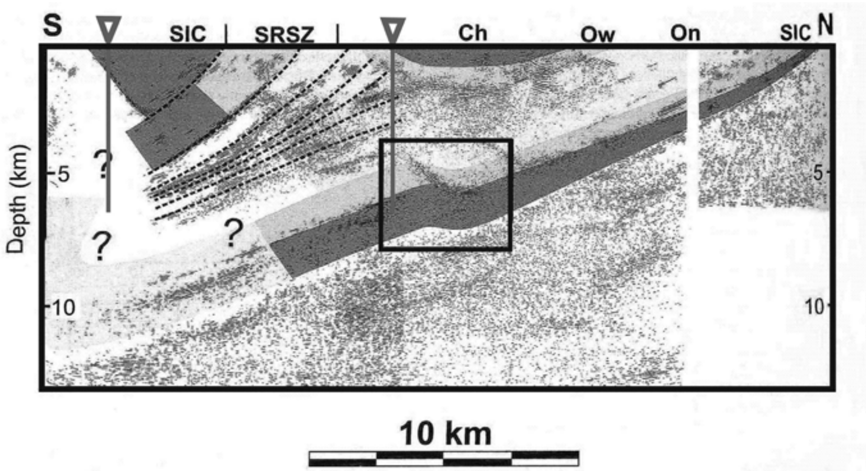

Fig. 19. Seismic image of the Sudbury structure with proposed deep drilling sites indicated (SIC = Sudbury Igneous Complex; On = Onaping Formation; Ow = Onwatin Formation; Ch = Chelmsford Formation; SRSZ = South Range Shear Zone).

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.

7.2 Further Drilling at the Chicxulub Impact Structure

A number of drillings of this structure, from hydrocarbon exploration and academic interest, had by the late 1990s proven beyond doubt that the Chicxulub structure on the Yucatán peninsula of Mexico is indeed of impact origin and at 65 Ma age represents the smoking gun for the environmental catastrophe and associated mass extinction at the global Cretaceous-Tertiary (KT) boundary. Much environmental modeling of this impact catastrophe ensued, as well as geophysical study and modeling of the crater structure itself.

As described above, in the late1990s, a multinational consortium initiated a large-scale drilling project by ICDP to investigate a whole range of objectives, foremost amongst which were groundtruthing the geophysical theory and numerical modeling results concerning the physicochemical processes associated with the cratering process that caused this global environmental catastrophe. It was anticipated that the drilling would produce a complete section through various impact breccias of the fill in the outer crater, as well as core through the critical biostratigraphic section at and just above the upper impact breccia fill. Tertiary post-impact sediment, 100 m of impactite, and a further 600 m of Cretaceous sediment below the crater were intersected and sampled. Much information regarding the origin of brecciated material from the evolving transient crater, its dispersal and deposition were obtained. In addition, many new questions were raised, including a controversial one about the exact positioning of the Chicxulub impact event with regard to the stratigraphic position of the KT boundary and extinction. The Cretaceous megabreccia below the impactites also raises questions as to its origin – in situ or as the result of massive repositioning during crater modification.

Many specific science questions, for example, the distribution of the meteoritic projectile and its admixture into impactite units, or the type of the meteoritic projectile, still remain to be resolved conclusively. However, the first-ever retrieved complete impactite section from such a large complex impact structure did allow scientists to generate a holistic hypothesis regarding the cratering and material dispersion process (material flow, dispersion, and modification). Drilling of Chicxulub represents the first such endeavor into a large, complex impact structure formed in the shallow marine environment.

A further important aspect of the study of this drill core, as well as of the entire Chicxulub Structure, is the extensive hydrothermal alteration that is observed throughout the studied materials. Hydrothermal activity has been shown in many impact structures to be of material benefit, with regard to formation of new economic ore deposits or its importance for the modification of pre-impact ore deposits (Grieve and Masaitis 1994; Reimold et al. 2005). Some new information about the original composition of the crust in the target region of the Chicxulub impact has also been obtained. Regarding the solution for many remaining scientific problems, including complete understanding of the 3D-crater structure, further drilling and extensive additional geophysical surveys are required. Regarding the debate about the biostratigraphy at and around the KT boundary and the exact stratigraphic positioning of the Chicxulub impact event, the Yaxcopoil-1 drilling has extensively stimulated the debate and fertilized the research of this problem by providing a somewhat disturbed but unique section of stratigraphy. Research of this aspect is still avidly pursued.

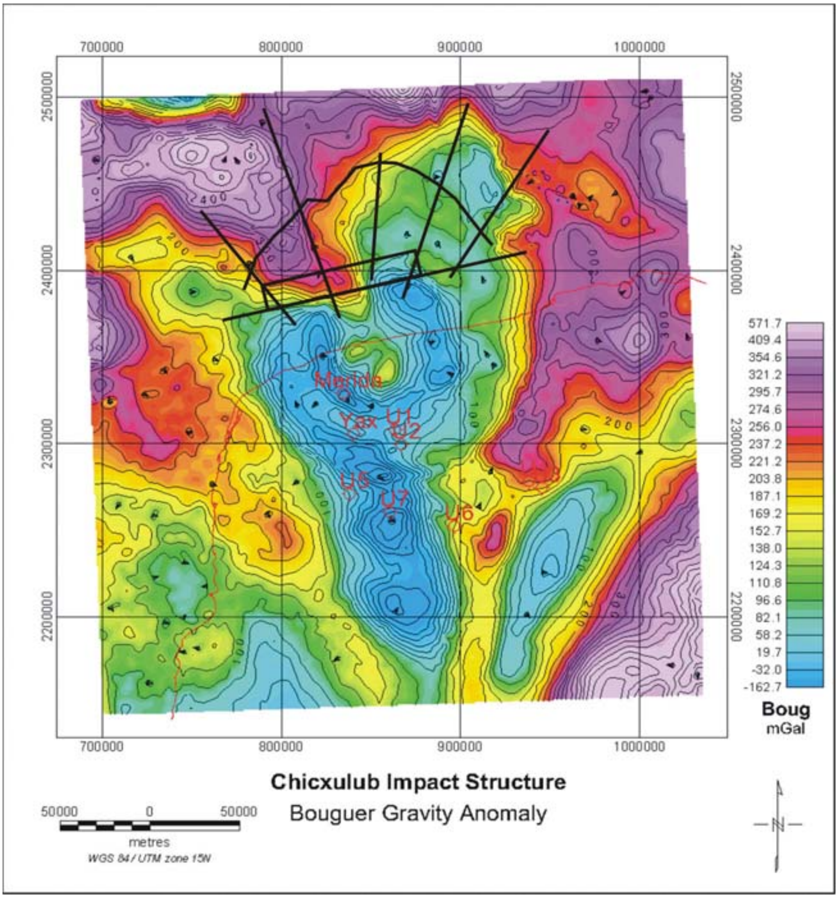

Fig. 20. Location map of the Chicxulub crater. Positions of some seismic lines and drill cores are also shown (after Morgan et al. 2005).

The mechanism that links the meteorite impact and mass extinction is far from clarified in spite of the extensive research conducted on the KT boundary impact during the last 25 years. The lack of such knowledge results mainly from the lack of a high-resolution record that covers the stratigraphic interval immediately after the impact (as well as the lack of spatial coverage of the high-resolution event record). Thick deep-sea tsunami deposits accumulated in proximal sites outside of the crater and corresponding thick resurge deposits inside the crater. The accumulation of these impact-induced deep-sea tsunami and resurge deposits started immediately after the impact and lasted for several days to weeks. The deposits thus preserve a high resolution record of accumulation of ejecta and dust.

Although a thick accumulation of the resurge deposits was discovered within the Chicxulub crater, it was demonstrated that the recovered sedimentary sequence is not complete but shows a hiatus near the top of the sequence. Such a hiatus probably developed through the formation of undulated bottom topography within the crater by sedimentation of suspended particles within the water column and subsequent erosion of the convex part of the bottom sediments through repeated agitation by tsunami waves. If this interpretation is correct, there could be areas within the crater where a continuous sedimentary record is preserved that covers the stratigraphic interval immediately after the impact with an ultra-high resolution in time. Such an ultra-high resolution sedimentary sequence will enable to reconstruct the accumulation of ejecta and dust immediately after the impact and will constrain the scenarios of impact winter or of the fires supposedly caused by reentry of hot ejecta.

For these reasons it would be interesting to drill inside the Chicxulub crater again in order to retrieve a thick continuous sedimentary sequence that preserves the sedimentary record immediately after the impact. A proposal has been submitted to the Integrated Ocean Drilling Program (IODP) to drill the peak ring and the exterior ring of the crater (Fig. 20). These drill cores will contribute to the determination of the size and morphology of the Chicxulub crater. A workshop to define the goals of a possible second Chicxulub deep drilling project was held in September 2006 in Potsdam, and was jointly financed by IODP and ICDP.

7.3 Kgagodi Basin (Botswana)

This 3.4 km diameter, still undated impact structure in eastern Botswana is the only meteorite impact crater known in the vast region of the Kalahari Desert of southern Africa. In 1997/1998, a hydrogeologic project in the region led to the recognition of the presence of a structure near the township of Kgagodi. This structure was thought to represent the intersection of two significant fault structures, which was then taken as a logical target for hydrological drilling. A gravity profile showed a rough crater form. A borehole was sunk to a final depth of 274 m, but the drilling location turned out to be only 400 m from the edge of the crater structure. Further geophysical investigations ensued. The drill core stratigraphy comprises 158 m of sediment, underlain by 5 m of breccia, and then, from 163 to 254 m, fractured Archean granitoid basement, followed by undeformed basement rock. Detailed petrographic analysis showed the presence of shock metamorphic deformation in clasts of the 5 m thick breccia layer, proving the presence of a meteorite impact crater. Paleontological attempts to obtain a stratigraphic age for the crater were inconclusive but suggested that the structure could be as old as 60 Ma – making it a preferred target for drilling into its center to obtain a continuous profile through the maximum thickness of crater fill (see Brandt et al. 2002). Besides the enormous paleo-climatic benefit of such drilling, access to the central impact breccia fill would provide a unique opportunity to compare the internal structure of Kgagodi with Brent Crater of near-identical size. Drilling is also required to obtain fresh impact melt to date the impact event with confidence. Drilling at Kgagodi could also provide an important geotourist and educational location along one of the main roads in Botswana. However, no progress has been made in recent years towards establishing a drilling project.

7.4 Mjølnir, Norway

The Mjølnir impact was formed in the very latest Jurassic, when a 1.5 to 2 km bolide impacted the about 400 m deep paleo-Barents Sea. The Mjølnir crater is presently located in a well studied area, covered in detail with both geological and geophysical information, to a large extent due to the intense international search of oil and gas in the area. The crater is located in the Arctic, surrounded by Canada, Greenland, Norway - Svalbard, Russia and the USA, where the geological structure and composition are well-known through years of detailed studies. In addition basic information about the crater structure and its general setting is fairly well known. The stratigraphic units, being of epicontinental affinity, are continuous over huge areas and several ways of stratigraphic dating can be applied to these shallow marine beds from the original 300-500 m deep sea (presently circum-polar). The sediments carry several mineralogical and geochemical signs of impact (traces have been found in the successions of Svalbard and Siberia), but they also contain macro- and micro-fossils.

The ejecta creating processes along with the post sedimentary effects close to the crater and in increasing distance from it, have been studied systematically to only limited extent. In order to be complete such studies will necessarily have to be widespread aerially and cover many different scientific subjects. Analyses of these impact effects should be performed on well dated structures where stratigraphical units in known successions can be found and accessed in wide areas around the crater. In addition to the new contributions to impact related process theories, this will also shed more light on the relationships between cratering and, e.g., the processes of ejecta distribution, tsunami formation, mass- and density flows, avalanches, etc. This would consequently need both international and interdisciplinary approaches to be solved. Marine impacts, such as Mjølnir, will most likely give the best results in this respect, as impacting occurs in layered sedimentary basins and often succeeded by well developed post-impact sedimentation. In such a case environmental effects of both subaerial and submarine processes along with, e.g., tsunami formation and propagation could be studied.

This project would surely trigger public interest and may also engage some of the oil companies active in the region. Because the Mjølnir crater is located below shallow sedimentary burial depths (50 –150 m) and 350 m of water, on the continental shelf in an oil and gas province, this would typically be a project demanding close ICDP/IODP cooperation.

8 Synopsis: Future Drilling of Impact Craters

Impact cratering is a fundamental process in the solar system. It reshaped the early surfaces of the terrestrial planets, and played a pivotal role in the evolution of life on Earth. The formation of impact craters and their effects can be understood by a combination of geological observations of the actual impact structures in the field on Earth as well as laboratory experiments and numerical modeling. The Earth is the only place in the solar system where impact craters can be studied in three dimensions on scales ranging from crater scale to microscopic scale. The 3D picture is essential in reconstructing the geological history of these features, from the time of formation through erosional modification and other deformation and alteration processes. Various aspects of the 3D picture on an impact structure can be obtained through geophysical data, which may yield non-unique interpretations and, thus, require groundtruthing and calibration by linking geophysical signals and responses with observations on the actual rocks. There are only two ways to do this: first, by outcrop studies, and, second, by drilling.

Early drilling operations, for example at the Brent crater in Canada, were essential to establish the internal structure of a simple impact crater. In addition, the concept of the transient crater was confirmed by such drilling data. In the 1970s, the drillings at the Ries crater in Germany were essential to establish the relationship between the pre-impact stratigraphy of the various rock types and the sources of the different breccia types (e.g., Bunte Breccia, and suevite). This, in turn, helped to understand the processes that operate during formation of a complex impact crater.

More recently, the Chicxulub drilling helped to establish the link between the geophysical data and the various rock types found in nearby-breccia, as well as provide further constraints on the timing relationship of the breccia deposition and the longer-term crater fill. The data from the Bosumtwi crater drilling are not yet published, but in terms of impact studies the abundance and distribution of melt-bearing breccias yielded surprises that require reinterpretation of the conclusions obtained from previous geophysical measurements. The drilling will also afford an understanding of the shock wave decay in the central uplift of this moderately sized complex impact structure; only very few such measurements are available so far.

Thus, previous drilling operations have been essential in linking numerical models and geophysical data on impact structures and their formation with the actual behavior of the rocks. No other methods can provide information on these important points that help to understand the impact process. Many details are still not clear, in part because of the large variety in target lithologies and impact parameters, and the very small number of impact structures that have so far been studied in detail. Therefore, it is important to continue drilling at impact structures, bearing the specific questions that are listed above in mind.

Scientific drilling of large craters will provide new 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.

Scientific drilling should focus on very large impact craters (Chicxulub, Popigai, Manicouagan, Sudbury, Vredefort) that occupy a vast volume of the continental crust and thus require deep drilling to recover representative samples through the structure. These structures are examples of multi-ring impact features on Earth and provide the only opportunity to study the internal stratigraphy and lithology distribution in these structures, which are otherwise only accessible on the Moon and other planets by remote sensing. In addition, these large impact craters will offer new insights into possible links to mass extinction events or can be utilized to determine the thresholds needed for extinctions to occur. In addition, it is important to note that impact craters provide physically defined basins that can provide a record of post-extinction recovery (in the larger events) and a record of evolutionary and climatic change over thousands to several million years, as well as an assessment of the post-impact thermal evolution of large volumes of crustal melt, the associated hydrothermal activity and its effect on the redistribution of economically valuable mineral deposits. It is important to note, however, that these studies will require multiple drill sites to fully map these complex processes.

Deep drilling of impact craters will provide new information about the Earth's deep biosphere. Bacteria are known to be present at depths as great as 4 km below the Earth's surface. The existence of a deep biosphere has profound implications for the origin and evolution of life. During the bombardment of the early Earth by bolides like those that produced the Vredefort and Sudbury structures, life may have survived only deep within the Earth. In future scientific drilling projects, fluids and gases need to be sampled within deep holes, and the recovered cores should be examined for traces of biological activity. Thus, deep drilling results of impact craters may provide a first glimpse of the deep limits of the biosphere. Craters of all sizes provide sediment catchments that should be exploited to better understand biologic evolution and changes in the regional climate. The Bosumtwi and El'gygytgyn projects are examples this type of study, which should be replicated at several other impact sites.

Clearly it is not necessary to drill dozens of craters, but it is more important to obtain a good representation of the different forms, sizes, and target materials, and explore specific craters in more detail than with just one drill core. Drilling into impact structures will continue to be the main source of material for new and detailed studies of impact crater materials and, therefore, greatly enlarge our knowledge of the impact process in general.

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Appendix 1. Status of Drilling at Canadian Impact Craters (R. Grieve, pers. comm. 2005).

Crater, Location	Details	Core Location
Brent, Ontario	5 km of core from 12 holes penetrate sedimentary fill, a brecciated zone, a melt zone & into fractured crystalline basement (Grieve and Cintala 1981).	GSC* (entire)
Carswell, Saskatchewan	Tona et al. (1985) include drill hole locations on plan map and show profiles of regional geology using these data.	Industry
Charlevoix, Quebec	1 km hole drilled by Abiogenic Fuels to look for abiogenic methane.	Industry
Clearwater East, Quebec	DDH 1-64 (~900 m deep) and 1-63 (~400 m deep) penetrated sedimentary filling complex and allogenic breccia. Located at 2 km and 3 km from the center, respectively (Dence 1968; Palme et al. 1979).	GSC (entire)
Clearwater West, Quebec	Five holes have been drilled within the island ring. General descriptions in Dence et al. (1965).	GSC (entire)
Deep Bay, Saskatchewan	Four holes drilled. Drill hole 62-1A penetrates shocked and fractured gneisses of central uplift and extends to depth of 433 m. Allogenic breccia was found to flank centrally uplifted rocks (Innes et al. 1964; Dence et al. 1968).	GSC (entire)
Eagle Butte, Alberta	Drilling, along with seismic surveys, has been used to detect the central uplift and the ”crater moat” (Ezeji-Okoye 1985).	Industry
Elbow, Saskatchewan	3 holes drilled by Imperial Oil, some in partnership with Tide Water Associated Oil Company. In centre 'Imperial Elbow 1' 12-25-23-6W3, eastern flank Tide- Water Imperial Elbow Crown 1, 1-25-23-6W3, and Tide-Water Imperial Elbow Crown 2 5-13-23-6W3 on a geophysical low at the base of the southern flank of the structure - all dry holes (Grieve et al. 1998).	Industry & Saskatchewan Geol. Survey (partial sampling)
Haughton, Nunavut	Seven auger holes, AH98-1 to 7 (6 m max depth of 6 m), totaling 29.35 m were drilled as part of the 1998 Mars-Haughton Project.	NASA Ames Research Center and the University of Toronto.

Holleford, Ontario	Three drill holes at distances of 430, 760 and 1140 m from the centre of the crater to depths of 340, 450 and 135 m, respectively, penetrate breccia (St. John 1968).	GSC (entire)
Manicouagan, Quebec	Central magnetic anomaly drilled by Manic Minerals- to a depth of ~500 m.	GSC (entire)
Maple Creek, Saskatchewan	07-07-101-23W3 near centre of structure (depth ~1400 m interpreted from seismic down hole log data), and two other 01-04 (depth ~1200 m) and 04-01 (depth ~1000 m) locations unknown (Grieve et al. 1998).	Industry & Saskatchewan Geol. Survey (partial sampling)
Montagnais, Nova Scotia	A single oil exploration well (Montagnais I-94) penetrated the central uplift (Jansa and Pe-Piper 1987; Jansa et al. 1989) down to a depth of 1,646 m.	Industry and GSC (partial sampling)
Saint Martin, Manitoba	Five holes, totaling 330 m were drilled into the crater, (McCabe 1977, 1983).	Manitoba Geol. Survey and GSC (partial sampling)
Steen River, Alberta	Anomalously shallow basement rock was encountered during wildcat drilling for oil. A cross-section of the structure with drill hole locations is found in Carrigy (1968).	Industry
Sudbury, Ontario	Extensive underground mining in connection with sulphide ores occurs within the Sudbury Igneous Complex.	Industry & sampling of three cores through SIC at GSC.
Viewfield, Saskatchewan	Shell Viewfield 'B' 13-30-7-8 W2M and United Canso Viewfield 8-30. 3 wells by Sask. Energy and Mines, 5-29, 13-29, 15-29-7-8 W2M max. depth 788 m below sl). Geodata Ltd drilled to 2265 m. Two rim wells (#1-33-7-8 W2 and #7-33-7-8 W2) and 23 wells along periphery of crater (Sawatsky 1972; Grieve et al. 1998).	Industry, Saskatchewan Geol. Survey and GSC (partial sampling)
West Hawk, Manitoba	Four bore holes were drilled into West Hawk Lake, 65-1 is closest to the crater center; holes 66-3, 66-2 and 66-1 are 260, 305 and 1159 m to the SW, respectively (Halliday and Griffin 1967).	GSC (entire)

* GSC - Geological Survey of Canada

Appendix 2. List of impact craters drilled in the former Soviet Union (V. Masaitis, Karpinski Institute, St. Petersburg, pers. comm. 2006).

Name	Country	Coordinates		Diameter	Number	Depth [m]	
		North	East	[km]	of Holes	Average	Maximum
1. Belilovka (Zapadnaya)	Ukraine	49°23'	29°03'	3.2	~50	300	500
2. Bigach	Kazakhstan	48°34'	82°01'	8	2	200	
3. Boltysh	Ukraine	48°55'	32°15'	24	>150	500	1150
4. Dobele	Latvia	56°35'	23°15'	4.5	~10	300	500
5. Gusev	Russia	48°26'	40°32'	3	20	400	2000
6. Ilyinets	Ukraine	49°07'	29°06'	8	~80	200	500
7. Kaluga	Russia	54°40'	36°07'	15	110	600	1100
8. Kamensk	Russia	48°21'	40°30'	25	>150	400	4000
9. Kara	Russia	69°06'	64°09'	65	~30	250	700
10. Karla	Russia	54°55'	48°02'	10	~15	200	500
11. Kärdla	Estonia	59°01'	22°46'	7	~30	100	600
12. Kurgantau	Kazakhstan	52°08'	62°06'	1.5	5	20	200
13. Kursk	Russia	51°42'	36°00'	6	5	300	500
14. Logoisk	Belarus	54°12'	27°48'	15	~30	350	1250
15. Mishina Gora	Russia	58°43'	28°03'	2.5	5	200	900
16. Mizarai	Lithuania	54°01'	23°54'	5	5	250	600
17. Obolon	Ukraine	49°39'	32°55'	20	5	600	1500
18. Popigai	Russia	71°38'	111°11'	100	500	300	1500
19. Puchezh-Katunki	Russia	56°58'	43°43'	80	330	300	5374
20. Ragozinka	Russia	58°44'	61°48'	9	5	200	500
21. Rotmistrovka	Ukraine	49°11'	31°45'	2.7	~15	150	400
22. Shunak	Kazakhstan	47°12'	72°42'	2.8	5	250	

The GeoBiosphere

Brian Horsfield[1], Thomas L. Kieft[2], and the GeoBiosphere Group*

[1]GeoForschungsZentrum Potsdam
Telegrafenberg, D-14473 Potsdam, Germany
e-mail: horsf@gfz-potsdam.de (corresponding author)

[2]New Mexico Institute of Mining and Technology
Socorro, NM 87801, USA

Abstract

Studies during the past two decades have demonstrated that the biosphere extends to great depths beneath the surface of the Earth's continents. This deep biosphere contains diverse and active microbial communities whose biomass may even exceed that of surface organisms. The distribution of these subsurface microbes is controlled by multiple interacting factors, e.g., porosity of sediments and rocks, temperature, pressure, energy and nutrient availability, and rates of geohydrologic processes. Progress in understanding life in the subsurface has been limited by available technology but also by funding. Knowledge of the deep biosphere is based on only a few boreholes and many fundamental research questions remain unanswered. While the International Continental Scientific Drilling Program (ICDP) has included geobiological components to some recent projects, there is an opportunity for even greater scientific contributions. We recommend that the ICDP follow the example of the Integrated Ocean Drilling Program (IODP), which now includes a biological component to every sampling mission and furthermore makes biological inquiry the central focus of several of its drilling campaigns. By addressing major questions in the geobiology of the subsurface, we anticipate that the ICDP will achieve

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*GeoBiosphere Group is: Hans Amann (Maritime Technology Group, Technical University of Berlin, Germany), Stephen G. Franks (Saudi Aramco, Dhahran, Saudi Arabia), Jens Kallmeyer (NASA Astrobiology Institute, University of Rhode Island, USA), Kai Mangelsdorf (GeoForschungsZentrum Potsdam, Germany), R. John Parkes (School of Earth, Ocean and Planetary Sciences, Cardiff University, UK), Dirk Wagner (Alfred Wegener Institute for Polar and Marine Research Potsdam, Germany), Heinz Wilkes (GeoForschungsZentrum Potsdam, Germany), Klaus-G. Zink (GeoForschungsZentrum Potsdam, Germany)

even greater prominence during its second decade and thus increase the potential for scientific contributions in all of the disciplines within subsurface science.

1 Introduction

The biosphere is the part of planet Earth inhabited by life. It occurs in three overlapping zones: the *lithosphere*, comprising soils, sediments and other rocks; the *hydrosphere*, that part of the lithosphere either covered by water or containing water (within pores and fractures); and the *atmosphere*, the gaseous envelope surrounding the Earth (Fig. 1). Most organisms rely on photosynthesis for their existence, either directly (primary producers) or indirectly via the food chain, and hence the greatest biomass inhabits the surface/near-surface lithosphere and shallow hydrosphere. Microorganisms make up a major component of the Earth's biomass because they can grow under a wide range of conditions and have diverse metabolisms. Aerobic bacteria use free oxygen to degrade and metabolise labile organic substrates, but where oxygen cannot penetrate, for instance through fine grained sediments, anaerobic microorganisms take over degradation using other terminal electron acceptors (oxidisers) such as sulphate, nitrate, manganese iron and carbon dioxide. Anaerobes are the dominant inhabitants of the lithosphere. Their abundance in sedimentary basins shows a general decrease with increasing depth, eventually petering out as organic matter becomes too recalcitrant to be degraded or because water, nutrients and terminal electron acceptors cannot be supplied or because temperatures are too high.

Conventional wisdom dictated that the biosphere was restricted to the top tens of metres in sediments, and that processes in deeper layers and higher temperatures (above 50° C) were purely abiotic (Tissot and Welte 1978; Killops and Killops 1993; Morita and Zobell 1955). Yet, surprisingly large bacterial populations are present at depths approaching 1000 m in some locations, and in this subsurface habitat there is considerable bacterial diversity (Parkes et al. 1994; Zlatkin et al. 1996; Ringelberg et al. 1997). Deep sediments are part of the ever-growing list of extreme environments, including glaciers, ice-sheets and buried lakes, deep water sediments, salt and ultra deep gold mines, gas hydrates, oil reservoirs, aquifers, confined and deep fractured rock, crustal fluids and hydrothermal vents, where microbial communities have been detected. The largely unexplored deep biosphere must play a fundamental role in global biogeochemical cycles over both short and longer time scales because its mass could be equal to that of the surface biosphere (Whitman et al. 1998; Pedersen 2000). Indeed, interest in the deep biosphere has grown exponentially in the last 10 to 15 years, fueled at least in part by the claim of microbial remains in Martian meteorites and questions regarding how microorganisms can live under extreme conditions, claims of microorganisms surviving for 100's of millions of years, by questions about interactions (beneficial and non-beneficial) of microbes on petroleum deposits in the subsurface (L'Haridon et al. 1995), by studies of deep nuclear waste disposal sites and deep aquifers, and of course simply by scientific curiosity. Excellent reviews on aspects of the deep biosphere have been published by Chapelle (1993), Lovley and Chapelle (1995), Parkes et al. (2000), and Head et al. (2003).

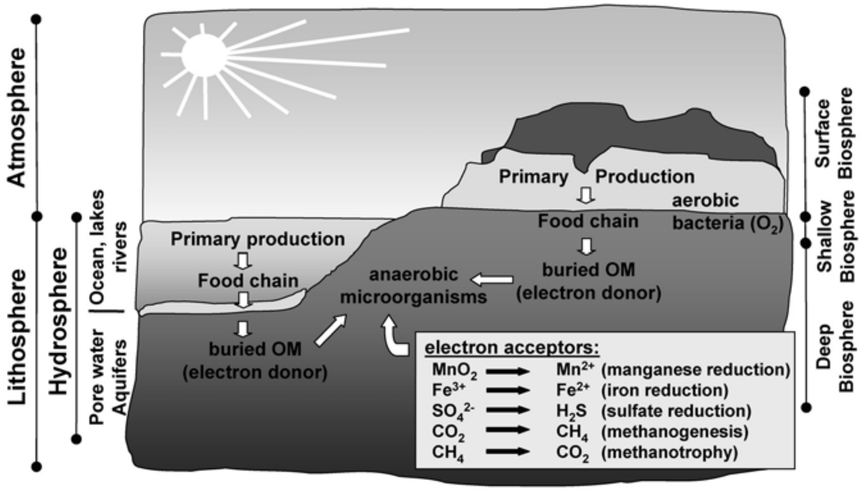

Fig. 1. Extension of the biosphere on Earth.

It has been estimated that 90% of the prokaryotic (bacterial and archaeal) cells in the Earth's biosphere exist in marine and terrestrial subsurface environments (Fig. 2; Whitman et al. 1998). It has even been posited that this deep biosphere harbours a greater biomass than the mass of all the living cells, prokaryotic and eukaryotic, in the surface regions of the biosphere (Onstott et al. 1999). These estimates of the extent of the deep biosphere have been made by projecting and extrapolating from data collected from a very limited number of boreholes in marine (for a review, see Parkes et al. 2000) and terrestrial (Hazen et al. 1991; Pedersen 1993, 2000) environments. In truth, we have only very limited data on which to base these estimates. The lower depth limit of the biosphere has not been reached in any borehole studies that have included a microbiological component, and the factors that control the abundance and activities of microbes at depth and the lower depth limit of life are still poorly understood. While the marine regions of the deep biosphere are now being systematically probed by the Integrated Ocean Drilling Program, the terrestrial deep biosphere is receiving somewhat less attention, and this is where ICDP must play the leading role (Fig. 3).

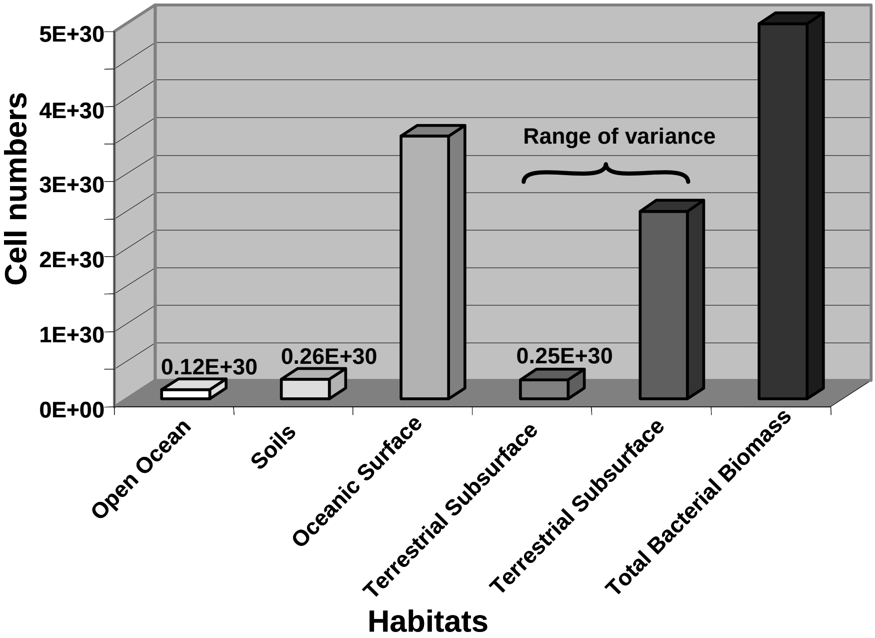

Fig. 2. Global prokaryotic biomass distribution, given in cell numbers (after Whitman et al. 1998).

2 Requirements of Deep Biosphere Organisms

We begin by giving an overview of what is known about the deep biosphere so we can later define the objects and processes which can be probed by drilling.

As with their human (eukaryotic) relatives, microorganisms need available "living space", liquid water and a ready supply of energy and essential nutrients to survive or thrive. Environmental parameters defining the dimensions of living space are ultimately dictated by the tectonostratigraphic setting at the time of deposition and during subsequent burial. Sediment distribution patterns, degree of sorting, and the nature of the erosional hinterland (lithology, prevailing climate) control initial matrix composition, porosity and permeability. Subsidence, uplift and deformation of the basin-fill control pressure (lithostatic, hydrostatic), and modify porosity and permeability of lithotypes. Additionally, microbial activity can itself result in the mineralizion/fossilization/cementation of the microorganisms themselves, other organisms and the environment (Coleman 1993; Sagemann et al. 1999). Basin style and evolution control temperature gradient, a critical control of deep biosphere occurrence.

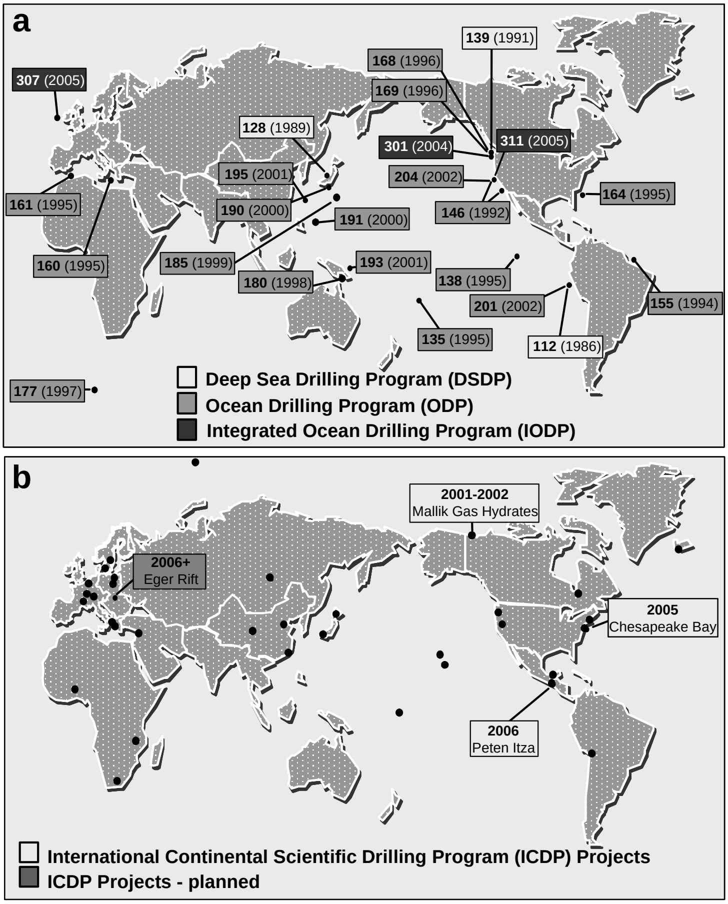

Fig. 3a. Map of DSDP, ODP, and IODP Legs (indicated by their numbers) considering microbial or deep microbial scientific objectives. **b.** Map showing completed and planned ICDP projects containing biogeochemical objectives. Black dots indicate ICDP projects where no biogeochemical objectives were included.

The provision of food (electron donors) and oxidants (electron acceptors e.g., oxygen), or more accurately energy and carbon sources, is controlled by the thermodynamic potential of chemical reactions, both organic and inorganic, including reactions close to thermodynamic equilibrium ($\Delta G'$ approximately 0 kJ mol^{-1}, Jackson and McInerney 2002). The rate at which these reactions can be microbially catalysed can be up to 10^6 times higher compared to abiological rates, depending on the rate of supply and removal of substrates and products, the concentration (above minimum thresholds and below toxic levels) and bioavailability of reactants and environmental conditions. The original chemical composition of the sediment and the response of microbes and its organic and inorganic components to increasing temperature are limiting factors. However, increasing pressure during burial may not be a major limitation as some microorganisms can cope well with high pressure (>100 MPa, Kato et al. 1998) and there is some evidence for metabolic activity at GPa pressures (Sharma et al. 2002). Microbes can survive, and even thrive, in the most extremes of environments, possibly only limited by the availability of liquid water (Rothschild and Mancinelli 2001), which if correct, makes the deep subsurface an extensive potential microbial habitat.

2.1 Living Environment

Microorganisms need pore space in which to live. The initial porosity of loosely packed (i.e., uncompacted and uncemented) sediments depends on sorting, grain shape, grain size, and sedimentation rates and can range from approximately 25-55% (by volume) for sandstones, 50-90% for shales and 40-95% for limestones, respectively (Poelchau et al. 1997). The decrease of porosity with depth is a function of overburden thickness, time, lithology, depositional environment, pressure development (including overpressuring), diagenesis, and tectonic stress (Chilingarian 1983). Water-filled fractures can exist even at extreme depths (Stober and Bucher 2004). Quartzose sandstones are more likely than feldspathic or lithic sandstones to maintain sufficient open space at depth, as they are both mechanically and chemically more stable thus less prone to compaction and cementation.

It is the type of pores within a rock and the degree to which they are interconnected that is a factor controlling deep biosphere occurrence, and not simply porosity. This is because microorganisms occupy only about one millionth of available porosity (Parkes et al. 2000). An adequate flux of liquids or gases through rock pores is required to sustain life (Colwell et al. 1997; Colwell and Smith 2004), and this is governed by pore throat dimensions. Permeability describes the ability of sediments to transmit fluids and/or gases, and is controlled by the effective porosity, the number and type of pore interconnections, and by the nature of the permeating fluid. This rock property regulates the pressure-driven transport of electron donors, electron acceptors, and nutrients to sustain living cells. Quartz arenites retain permeability to great depths and offer perhaps the most stable living accommodation for microorganisms. In contrast, the high reactivity of unstable volcanogenic sandstones and their mechanical weakness make them susceptible to rapid porosity and permeability loss, in some cases at relatively low temperatures. Fractures are orders of magnitude more permeable than pore systems. In some cases, deep fractures contain ancient water that has been geohydrologically sequestered from other ground water for millions of years (Lippmann et al. 2003). Life in such isolated pockets of groundwater may be constrained to a very few cells with low rates of activity (Kieft et al. 2005), or they may even represent "dead" zones (Colwell and Smith 2004).

The currently known upper temperature limit for life anywhere in the biosphere is 121°C (Kashefi et al. 2003). This upper limit has been climbing to higher and higher temperatures over the years as new extremophiles are cultivated from increasingly hot environments. One can speculate that the actual upper temperature for life may be somewhat greater than 121°C, but the consensus among microbiologists is that the ultimate upper temperature limit for life on earth is not more than a few degrees above 121°C, although temperatures as high as 150°C have been considered (Deming and Baross 1993) and survival temperatures are higher than growth temperatures. Temperature is defined by the product of heat flow and thermal conductivity. Extensional basins exhibit the highest heat flows especially where active rifting is taking place, whereas lowest values are seen in shield areas and some compressional settings (Allen and Allen 1990). Consequently, geothermal gradients usually fall in the range 10 to 60°C km^{-1} (Philpotts 1990). Combining the upper temperature limit for life and geothermal gradients with mean surface temperatures of 0-25°C to estimate the extent of life yields a depth range for the biosphere of 2 to 12 km below land surface (kmbls). This is not to say that all microorganisms can survive up to that temperature; the upper limit for in-reservoir petroleum degradation appears to be 80°C (Wilhelms et al. 2001).

Cold subsurface terrestrial environments may be similarly important, if not more important, than hot subsurface environments as microorganisms have been found in a range of cold subsurface environments including glaciers, ice sheets and permafrost, which cover substantial areas of land (Parkes and Wellsbury 2004; Priscu and Christner 2004). Permafrost can contain significant concentrations of gas hydrates and gas hydrate containing sediments can have enhanced subsurface microbial activity and populations (Wellsbury and Parkes 2000).

2.2 Mass Fluxes: Key to Understanding Life in the Deep Biosphere

Geochemical modelling has estimated the rates of microbial activity in aquifer sediments to be orders of magnitude slower than those in surface environments (Chapelle and Lovley 1990; Phelps et al. 1994; Parkes et al. 2000), with corresponding average microbial generation times of hundreds to thousands of years (Phelps et al. 1994). Rates of activity in thick unsaturated (vadose) zones, fine textured aquitards, and the fractures of deep consolidated rock have been estimated to be slower by further orders of magnitude (Phelps et al. 1994; Kieft and Phelps 1997). Low rates of energy flux may limit the abilities of microbes to cope with the other stresses of subsurface life, e.g., high temperature and high pressure. More specifically, low energy flux in a thermal environment may be insufficient to fuel cellular maintenance (e.g., DNA repair), even though the temperature is below 121°C.

In the case of progressively subsiding sedimentary basins, organic matter produced at the surface by photosynthesis has generally been considered to be the dominant source of energy and carbon for microbial life in the terrestrial subsurface (Chapelle 1993). Most of the near surface microbial biomass is sufficiently motile as to avoid being buried during sedimentation, remaining where degradable carbon sources are abundant, but a significant number are carried into the geochemical part of the carbon cycle where organic matter quality becomes progressively poorer (Parkes et al. 2000). Rising subsurface temperature may overcome the inherent problem of organic matter quality and promote microbial activity throughout the main reaches of the deep biosphere depth window (Fig. 4). It may activate the carbon source, making it more readily degradable to microorganisms (Wellsbury et al. 1997) or cause the carbon source to thermally decompose into small organic molecules, which are then metabolized by the microorganisms (Horsfield et al. 2006). In the latter case rates of generation are very low, and, not inconsequentially, equal to that published for deep biosphere respiration, ca. $1*10^{-5}$ to $1*10^{-8}$ mg organic compounds g^{-1} sediment $year^{-1}$. Interbedded shales and porous sandstones provide a fertile ground for microbial colonization, especially at lithological boundaries (e.g., Krumholz et al. 1997; Onstott et al. 1998). Infiltration of deep sediments by migrating brines can stimulate renewed sulphate reduction (Parkes et al. 2005). Sometimes petroleum, which has migrated vertically and laterally far away from its shale source is biodegraded, either during migration through porous carrier systems (Horsfield and McLimans 1984) or at the oil-water contact in the reservoir itself (Head et al. 2003). In the latter case, the rate of degradation could be limited by the supply of nutrients and electron acceptors through the water phase (Larter et al. 2003) or by the replenishment of electron donors through the oil phase.

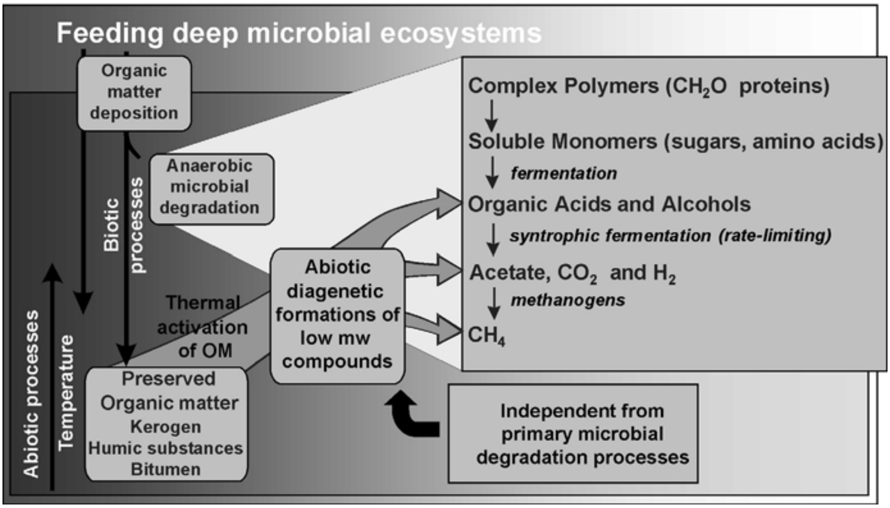

Fig. 4. Scheme visualizing potential carbon and energy sources of deep microbial ecosystems. OM = organic matter, mw = molecular weight.

The mineralogy of the deposits, which potentially host the microbial communities, is not inactive. Curtis et al. (1985) have suggested that oxidized iron phases (e.g., hematite, goethite) could be the precursors of diagenetic chlorite rims in quartz sandstones as suggested by the common occurrence of iron oxide inclusions in the rims. In non-sulfidic diagenetic environments, or where the amount of iron exceeds that available to react with all the sulphur, ferric iron may be buried with the sediments into the deep biosphere. There, amorphous phases may first recrystallize to hematite or combine with silica and other ions to form ferric iron clays (e.g., Fe^{3+}-rich smectite or illite) then undergo reduction to ferrous clays such as chlorite/smectite and ultimately chlorite. These ferric clay minerals and iron oxide grain coatings are potential sources of Fe^{3+} for microbial utilization. It is even possible that microbial reduction of Fe^{3+} could enhance or accelerate the reactions to chlorite or chlorite/smectite. Onstott et al. (1998) and Boone et al. (1995) have described dissimilatory Fe^{3+}-reducing bacteria in rock samples from depths approaching 2800 m and a temperature of 76° C in Triassic sedimentary rocks of the Taylorsville Basin in

Virginia, U.S.A. Onstott et al. (1998) suggest that these microorganisms may be utilizing Fe^{3+} present in diagenetic illite, as this appears to be the only source of oxidized iron in the sediments. How microorganisms gain access to solid iron oxides is problematical, but microbial reduction of structural iron in smectite has been demonstrated in laboratory experiments (Kostka et al. 1996; Gates et al. 1993). Outer-membrane c-type cytochromes, chelators that solubilize Fe(III), electron-shuttling compounds and pili transferring electrons from the cell surface to the surface of Fe(III) oxides have all been demonstrated (Lovley et al. 2004; Reguera et al. 2005). In addition, microbial iron and manganese reduction has shown to be important in deep marine sediments (D'Hondt et al. 2004)

In contrast to quartzose sandstones, arkoses may require no special grain-rimming components to provide microbes with the key ingredients for life. K-feldspars are a source of ammonium (NH_4^+) as well as phosphorus (P) under some conditions and a number of studies have clearly demonstrated the ability of microbes to preferentially attack K-feldspar grains (Hiebert and Bennett 1992; Hutchens et al. 2003), even to the point of singling out P-bearing apatite inclusion within them (Rogers et al. 1998). In theory, it would seem that the potentially richest source of nutrients for microbial growth in the subsurface would be lithic volcanogenic sandstones. Iron-rich clays and especially ferric oxide grain coatings not only provide a source of Fe^{3+}, but also contain significant amounts of P scavenged from sea water (Berner 1973). Reflecting these differences in lithology there are distinctly different populations in deep volcanic ash layers (tens of thousands of years to hundreds of thousands of years old) compared to communities in more abundant pelagic clays (Inagaki et al. 2003).

Silicic volcanic rocks such as rhyolite and dacite contain 800 and 1500 ppm P_2O_5, respectively, and andesites and basalts contain as much as 2600 to 4500 ppm (Spock 1962). Therefore, the alteration of volcanic glass (Fisk et al. 1998) and rock fragments to clay minerals and zeolites within the deep biosphere has the potential to provide a source of both phosphorus and nitrogen for microbial utilization.

Abiogenic CH_4 and other low molecular weight alkanes (ethane, propane, butane) can also be generated by water-rock interactions and have been reported in deep Precambrian environments (Sherwood Lollar et al. 2002). Rock-water interactions have also been reported to generate hydrogen that serves as the energy source for deep subsurface microbial communities that exist independent from photosynthetically derived organic carbon (Sherwood Lollar et al. 1993; Stevens and McKinley 1995, 2000; Chapelle et al. 2002; Lin et al. 2005a, b). Abiotic rock-water interactions that generate H_2 include serpentinization of ultramafic rocks (Coveney et al. 1987), oxidation of ferrous silicate minerals in basaltic aquifers (Stevens and McKiney 2000), and radiolysis of water in environments with significant gamma radiation flux (Hoffman. 1992; Lin et al. 2005). Abiotically generated H_2, CH_4, and other short chain hydrocarbons (sometimes termed "geogas"), all potentially serving as energy sources for deep subsurface ecosystems, deserve further investigation and characterization.

2.3 Dynamics of Factors Limiting to Life

If entombed within the deposited sediments, deep microorganisms should be the lineal descendants of the microorganisms originally present in the surface sediment and thus, intriguingly, this community would have survived and replicated over millions of years in the same sediment layer. With the passage of time, the organisms must have evolved completely separately from their shallow biosphere counterparts. The living environment and the availability of carbon and energy sources would have been defined by changing geological circumstances. For instance, exposure to progressively increasing temperatures would likely have stimulated growth at first (Wellsbury et al. 1997), but later on could have sterilised the sediments (Wilhelms et al. 2001). Subsequent uplift during basin inversion could offer new opportunities for microorganisms as the sources and sinks of electron acceptors and donors change in response to regional flow along new symmetries and the response of components in the system gas-water-oil to changing pressure and temperature conditions. Geological evolution is clearly complex, and the factors which have a direct bearing on the deep biosphere and the rest of the carbon cycle include (after Poelchau et al. 1997):

- Rate(s) of subsidence, uplift and deformation of basin-fill,
- Paleogeography; paleobathymetry; paleoclimate,
- Depositional conditions and products (i.e., sedimentation rates, environments, facies, organic matter accumulation),
- Hydrodynamics (fluid pressure distribution and patterns),
- Rock properties, such as porosity, permeability, density, thermal conductivity, heat capacity, compressibility,
- Fluid properties (water, oil and gas), such as composition, density, viscosity,
- Heat transfer (conduction and convection); i.e., thermal history,
- Organic matter transformation reactions; kinetic processes,
- Redistribution (transport) of fluids, especially primary and secondary migration of oil and gas,

- sequestering and trapping mechanisms (stratigraphic and structural traps, seal integrity, potential for clathrate formation).

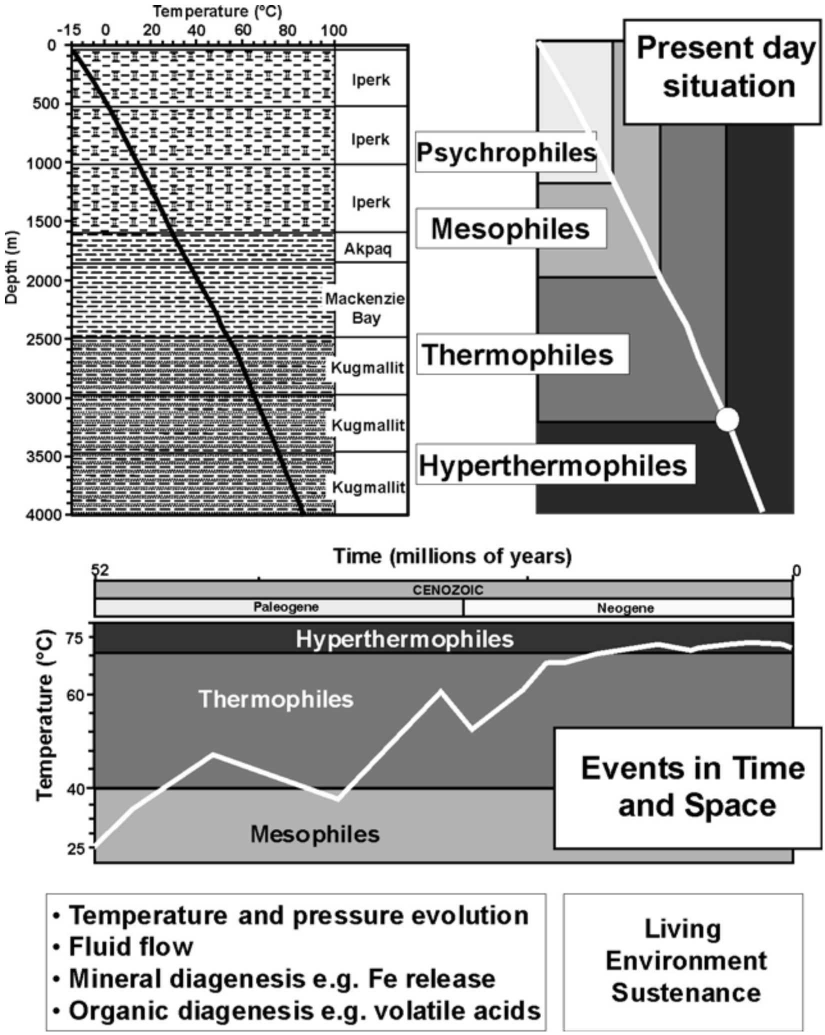

Fig. 5. Temperature profiles like the one at the top left are well known in the geological community. Less well known is the fact that microorganisms can live in all temperature ranges up to and including 120°C (top right). During subsidence and uplift, illustrated at the bottom, temperatures and indeed other life-controlling variables change, thereby influencing the distribution and diversity of subsurface communities over time.

The workings of the deep biosphere not only in space but also in time are of paramount importance for the petroleum industry (Fig. 5), where the advantages of discovering biogenic gas versus the disadvantages of discovering biodegraded oil have to be weighed up economically and environmentally. The past Earth as well as the present Earth has to be addressed as part of ICDP’s deep biosphere drilling initiative.

3 Major Questions Concerning the Deep Biosphere

The 1994 report of the workshop that initiated the ICDP (Zoback and Emmermann 1994) outlined the recent finding in deep subsurface microbiology (mainly of the U.S. Department of Energy’s Subsurface Science Program) and then outlined some of the key questions that had been raised by that pioneering research. Perhaps surprisingly, we can generate a very similar list today in that most of these questions remain unanswered. They remain unanswered in part because they are broad, fundamental questions requiring more than a decade to address comprehensively, and in part because there have been very few funded programs dedicated to addressing these questions. Our list below has been informed by the 1994 list and also by reports from other workshops to address the opportunities and challenges in deep subsurface geomicrobiology, e.g., the proposed Deep Underground Science and Engineering Laboratory (DUSEL) Site Independent Study (www.DUSEL.org) and EarthLab (www.EarthLab.org). The Integrated Ocean Drilling Program (IODP) identified two overarching questions when they made the deep biosphere one of the centerpieces of their scientific efforts. In their “Initial Science Plan, Oceans Earth, and Life Scientific Investigation of the Earth System Using Multiple Drilling Platforms and New Technologies”, they asked: “what is the extent of Earth’s deep biosphere and what is the character of the extreme life forms populating it?” (www.IODP.org). We ask the same fundamental questions, but include the dimension of geological time to address Earth history and evolution, reflecting on “what was”, and not just “what is”. More specifically:

- What are the factors that stimulate or limit life in the deep subsurface?
- What energy and carbon sources are available in the deep subsurface, and how do fluxes change as part of sedimentary basin evolution?
- Can we predict electron acceptor/donor generation from mineral diagenesis?
- Can we predict electron donor/acceptor generation from organic diagenesis?

- What are the fluxes across lithological boundaries?
- What is the importance of “Geogas”?
- What are the sources and rates of H_2 generation?
- What are the in situ rates of metabolism and how does this vary with different geological settings, depths and formation age?
- What are the biomass, growth rates and rates of evolution in the deep terrestrial biosphere?
- What types of organisms are in the subsurface and are they unique deep biosphere organisms?
- Is there a global deep biosphere common to both subsurface marine and terrestrial sediments which can inoculate formations during burial?
- What is the spatial heterogeneity in diversity of microbes in the subsurface (i.e., a map of the diversity of the subsurface)?
- What is the temporal diversity in a given subsurface location?
- Are deep biosphere organisms exploiting all low temperature (<121°C) parts of the rock cycle, is there overlap between biogenic and thermogenic processes, and if so, what are the consequences of this?
- What is the impact of the deep biosphere on global geochemical cycles and climate?
- What roles do subsurface microbes play in the formation and destruction of natural resources (conventional gas reservoirs, coal bed methane, biodegraded oil deposits, ore bodies, etc.)?
- How does the metabolism of indigenous communities influence subsurface geochemistry and mineralogy?
- Which biochemical mechanisms are employed by these organisms (with implications for biotechnology)?
- What adaptations do microbes have that enable persistence for geologic time periods under extreme conditions (e.g., low nutrient flux, high temperature, extreme pH, high pressure)?
- How do subsurface microbes maintain/repair macromolecular structures under extreme conditions?
- Could the subsurface have been the site for the origin of life or a refuge for early life during Hadean bombardment?
- Can subsurface microorganisms provide insights into the potential physiologies and habitats of early life on Earth?
- Are these ecosystems suitable analogs for possible subsurface life on other planets?

4 Technical Challenges Concerning the Deep Biosphere

Technical challenges go hand in hand with research objectives and drilling operations as far as the deep biosphere is concerned. Contamination by surface organisms has always been an issue (Fredrickson and Onstott 1996; Kerr 1997), and has ultimately led to the development of sophisticated controls and monitoring methods in geomicrobiology (Phelps and Fredrickson 2002; Kieft et al. in press). That bacterial cell counts (per cm^3 of sediment) in subsurface environments are 2 to 4+ orders of magnitude lower than at the surface makes the task at hand extremely difficult. Contamination control is an issue of paramount importance as far as the reporting of credible results is concerned.

Over the last few years several different techniques have been used to drill cores for microbiological investigations (Fig. 6). In the marine environment, the Ocean Drilling Program (ODP) has been a significant source of samples, and several studies have investigated the usefulness of the techniques applied (Parkes et al. 1995; Parkes et al. 2000; Smith et al. 2000). For terrestrial drilling operations, sampling for subsurface microbiology has been conducted by many different techniques, including air rotary- and cable tool percussion drilling (Colwell et al. 1992; Frederickson et al. 1995), but mud rotary drilling is most common for depths greater than ca. 40 m. The mud serves to cool the bit, remove cuttings and, by way of fluid pressure, prevent the hole from collapsing. Typically a suspension of clay minerals, usually bentonite, is used. For deep holes or where significant formation fluid pressures are expected, heavy minerals such as barite and organic emulsifiers are added. In order to obtain undisturbed sediment samples for detailed analyses, a core barrel is essential to maximise recovery, minimise the disruption of strata, and enable transport of the cored material up to the surface.

The mud used in rotary drilling can complicate the sampling of subsurface microbial ecosystems, simply because it can contaminate the core with surface microorganisms. The mud must be circulated at a pressure such that it is capable of removing cuttings, cooling the bit and maintaining the integrity of the hole. However, excessive mud pressure at the bit can cause the sediment to be saturated with drill mud several centimetres ahead of the bit. Drilling mud can also contaminate the core within the barrel because some drilling mud will always be present between the core and the barrel or core liner, and this mud can seep inwards and contaminate the inside of the core. Additionally, mud may penetrate into the core along fractures that might result from the stresses experienced during coring. Some degree of contamination may be expected for all cores collected by rotary drilling. Contamination control, therefore, is the technologically appropriate strategy.

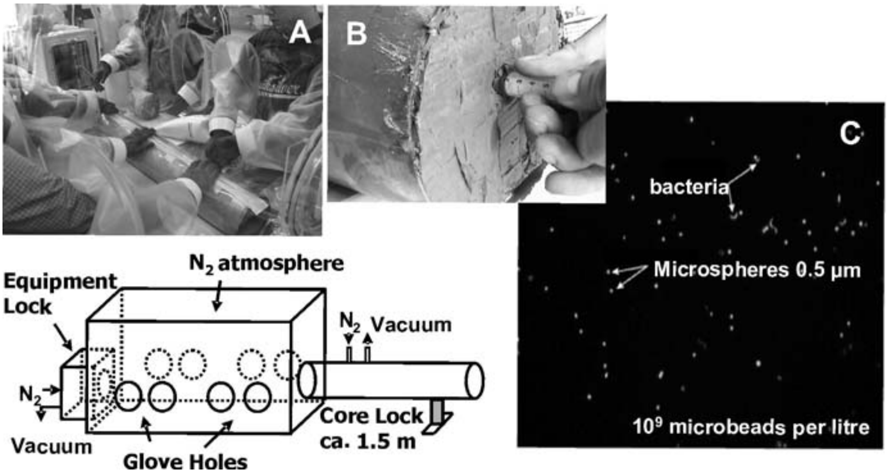

Fig. 6. Sampling under anaerobic conditions in an extended glove box (200 x 80 x 90 cm): A) Sampling of an 1 m subcore introduced under N_2-atmosphere into the glove box to collect appropriate samples for biogeochemical and microbiological investigations; B) Subsampling from centre of cores to control for potential drill mud contaminations by using fluorescent microspheres which were added to the drill mud and C) can be recognized under a fluorescent light microscope (photo by B. Cragg, Cardiff University).

Various methods for determining the extent of contamination have been described in the literature, and many involve a tracer added to the mud, which is not present in the sediment or pore water. The materials used are:

- Fluorescent microspheres (Fig. 6), which have the same size as a bacterium (Kallmeyer et al. in press; McMahon and Chapelle 1991a),
- Fluorescent microorganisms (Juck et al. 2005),
- Various chemical tracers, e.g., lithium bromide, dyes, barium (Chapelle and Lovley 1990; Haldeman et al. 1995; Pedersen and Ekendahl 1990; Pedersen et al. 1997; Phelps et al. 1989),
- Highly volatile inert compounds, which can be detected by headspace analysis after mixing a sample with water, e.g., perfluorocarbon tracer (House et al. 2003).

Molecular techniques can be used to infer the degree of contamination. Pedersen et al. (1997) used 16S RNA analysis to compare samples taken from the equipment, drilling muds and the deep sample to distinguish whether any contamination has occurred. Lehman et al. (1995) used fatty acid analysis to distinguish microbial communities in the drill fluid and in all of the drilled samples. If care is taken, relatively uncontaminated samples can be collected, and indigenous microorganisms can be distinguished from surface contaminants (Parkes et al. 1995).

In order to obtain undisturbed samples, core samples have to be uncoupled from the mechanical actions of the drill bit and the drill string. Wire line operated coring tools are used to achieve this. They are launched through the drill string, latch into the bottom hole assembly, core ahead of the hole, through the drill bit, and, finally, are retrieved through the drill string, which remains in the hole, and continues drilling ahead. Specialised tools have been developed for collecting and sub-sampling cores under in-situ conditions (Amann et al. 2004).

Two wireline pressure coring tools (HYACINTH coring systems) were designed and built as part of the European-funded HYACE project (HYdrate Autoclave Coring Equipment) and refined during the subsequent HYACINTH project (Deployment of HYACe tools In New Tests on Hydrates). It is beyond the scope of the current article to go into details of technical design, but both these tools enable core to be recovered and retained up to a maximum pressure of 250 bar (3,625 psi) using specially designed valves. The corers have been designed to allow the core to be transferred, without loss of pressure, into laboratory chambers for study and analysis. Because both the tools use ‘dry’ cutting mechanisms in a nonrotating drill string, they probably take relatively uncontaminated samples when compared with other tools that flush the bit with drilling mud or water. The Fugro Pressure Corer (FPC) was designed and built by Fugro Engineers BV in The Netherlands. It is a percussion corer that uses a water hammer driven by the fluid circulation to drive the core barrel into the sediment up to 1 m ahead of the drill bit, and is suitable for sampling unlithified sediments ranging from soft or stiff clays to sandy and gravelly material. It acquires a core 57 mm in diameter and up to 1 m in length in a plastic liner. The HYACE Rotary Corer (HRC) was designed and built by the Technical University of Clausthal and the Technical University of Berlin in Germany. It uses a downhole motor driven by the fluid circulation to cut a core up to 1 m ahead of the drill bit in lithified sediment or rock. It acquires a core 51 mm in diameter and up to 1 m in length in a plastic liner.

A whole family of connecting chambers has been developed to enable the core to be released and removed from the corer and transferred into measurement or storage chambers while still under full pressure (up to 250 bar). Once the core has been removed from the corer, a versatile manipulator system enables the core to be transferred between chambers for measurement of P wave velocity, gamma density, 3D electrical resistivity, P and S wave velocity, and shear strength, as well as for analysis by a portable X-ray CT system. When a pressure core has been logged at *in situ* pressure, it can then be slowly and incrementally depressurised to measure total gas content.

Other important systems enable sub-samples to be cut from a core and transferred into smaller chambers. The smaller sub-sample chambers can be connected to a microbiological system of chambers, where the central part of the sub-sample can be extruded in a sterile manner and cut into slices for studying barophilic micro-organisms and processes by culturing them under pressure (Amann et al. 2004).

5 Addressing Deep Biosphere Questions by ICDP Drilling

5.1 Recent/current Deep Biosphere-related ICDP Projects

As alluded to above, Zoback and Emmermann (1994) recognised that the Deep Biosphere was a hot research topic when laying out their rationale for ICDP. But there are only a few concrete examples where the leap of faith was made, employing geomicrobiology and biogeochemistry to deliberately search for deep microbial ecosystems. The Mallik 5L-38 well, drilled through terrestrial gas hydrates in Arctic Canada during the winter of 2001/2, was the first, followed by three projects feature deep biosphere research, namely the Chesapeake Bay impact structure (USA), Lake Peten Itza (Guatemala), and the planned Eger Rift (Czech Republic) project. A brief synopsis is as follows:

5.2 Mallik 5L-38 Gas Hydrate Research Well (2002)

5.2.1 Proponents

Dallimore, S. R. Geological Survey of Canada; Yonezawa, T. Japan National Oil Corporation (JNOC); Collett, T. S. U.S. Geological Survey; Uchida, T. Japan Petroleum Exploration Company; Weber, M. GeoForschungsZentrum Potsdam, Germany; Chandra, A. Ministry of Petroleum and Natural Gas (MOPNG), India.

5.2.2 Overview

Natural gas hydrates represent an immense hydrocarbon resource underlying large portions of the world's arctic continental areas and continental shelves. While these deposits ultimately may yield important sources of energy for the world, scientific and engineering research needs to be undertaken to make their production feasible. In addition to these very practical interests, there is mounting evidence that natural gas hydrates have had a very significant role in enhancing the pace of global climate change through the release of methane.

The Mallik 5L-38 Gas Hydrate Production Research Well is located at the northern edge of the Mackenzie River Delta, Northwest Territories, Canada. The predominant features of the Mallik site are a massive permafrost zone in the upper ca. 600 m and a zone of numerous gas hydrate bearing layers from about 896 to 1100 m. The scientific and engineering research objectives for the production research well focus on two themes: (1) the assessment of the production and geotechnical properties of gas hydrates, and (2) an assessment of the stability of continental gas hydrates to climate change. Among other things, cross hole tomography and logging were employed to delineate hydrate zones before and after dissociation was initiated. On-line monitoring of gas compositions (chemical and isotopic) was employed. Samples were collected during the drilling programme for biogeochemical and microbiological analyses.

5.2.3 Deep Biosphere Perspectives

To search for a viable deep microbial ecosystem in the Mallik well and to examine the potential of microorganisms to generate the Mallik gas hydrates were the goals. Although in low abundance, specific molecular markers (phospholipid esters from bacterial membranes; Fig. 7) for viable microbial organisms were detected in the Mallik sediments indicating the presence of a deep microbial community (Mangelsdorf et al. 2005). Additionally, a series of specific compounds may point especially to a microbial community of archaea (methanogens or methanotrophs). The latter confirms microbiological results for the previous Mallik 2L-38 research well drilling campaign (Colwell et al. 1999), which also indicated the occurrence of archaea (methanogens), and with the observations of Jain et al. (2003) during the 5L-38 Mallik project showing also the presence of methanogens. However, the low abundance of these molecular indicators together with the isotopic carbon signal of the gas hydrates demonstrate that the gas hydrate was generated by thermal sources.

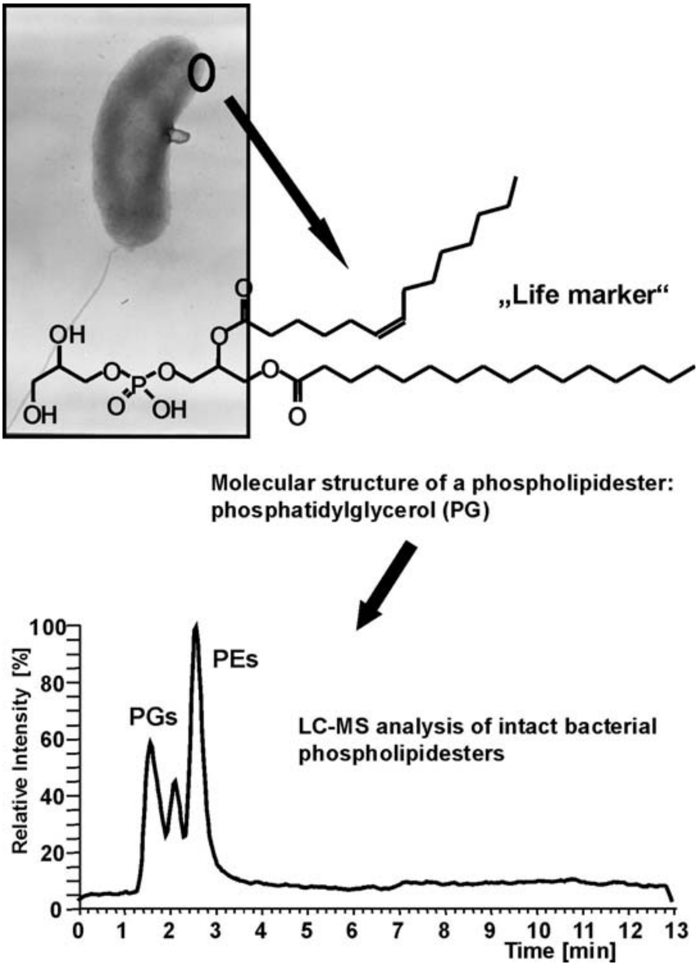

Fig. 7. Sketch visualising the context of deep buried microorganisms and detection of their membrane lipids as "life markers"; PE: phosphatidylethanolamine. The picture shows the bacterium LT25 (99% similarity with *Vibrio diazotrophicus*) isolated from deep sediments of ODP Leg 190, 297 mbsf (provided by L. Toffin).

5.3 Chesapeake Bay

5.3.1 Proponents

Gohn, G. U.S. Geological Survey; Koeberl, C. University Vienna, Austria; Miller, K. University of Rhode Island, USA; Reimold, W. U. Witwatersrand University, South Africa.

5.3.2 Overview

The late Eocene Chesapeake Bay impact structure is among the largest and best preserved of the known impact craters on Earth. A multidisciplinary and international drilling project at this crater, involving an international research team, was completed in fall 2005. Research topics included studies of impact processes, regional basin evolution, hydrogeology, borehole and regional geophysics, and the deep biosphere. The subsurface structure of the Chesapeake Bay crater was constrained by several shallow coreholes, over 2,000 km of marine seismic-reflection surveys, and gravity analyses. Major subdivisions of the structure are a circa 38-km-diameter central crater enclosed by a 24-km-wide annular trough. Several characteristics make the Chesapeake Bay structure unique among subaerial and submarine impact craters on Earth: (1) it is associated with the North American tektite strewn field, (2) it had a multi-layered, (rheologically varied) marine target; (3) it is a well-preserved and relatively young structure compared to most large terrestrial craters; (4) its location on a passive continental margin has prevented the tectonic disruption that is typical of many large terrestrial craters; (5) its original location on a relatively deep continental shelf allowed marine deposition to resume immediately and bury it rapidly and completely, thereby preventing subsequent erosion; (6) the upper part of the breccia section inside the crater was derived from resurge currents and impact-generated tsunami waves; (7) the breccia body may contain a large volume of impact-generated brine; and (8) the crater underlies a densely populated urban corridor, whose two million citizens are still affected by crater-related phenomena, specifically the presence of salty ground water within the structure. Thus, a 2.2-km-deep corehole was drilled near the central uplift within the “moat” of the structure’s central crater (as defined from seismic and gravity data) to obtain as thick and undisturbed a post-impact succession as possible, to collect a thick section of impactites, and to reach the sub-crater basement to study the shock barometry and fracturing of these rocks.

5.3.3 Deep Biosphere Component

The Chesapeake Bay Impact Structure provides an opportunity to understand the effects of asteroid and comet impacts on deep subsurface microbial communities. In the case of Chesapeake, impact volatilization of sea water may have generated pockets of briny fluids, which may influence microbial physiology. Impact events fracture rocks and potentially alter porosity and permeability. In the case of surface microbial communities, this increase in permeability may provide opportunities for endolithic colonists, but in the subsurface, where nutrient and redox couple limitations may be important, it is not clear that impact-induced changes in rock porosity and permeability will play a significant role. Studies on the microbial numbers, diversity, and physiology of organisms in the subsurface of the structure will provide opportunities to examine some of these questions.

5.4 Lake Peten Itza

5.4.1 Proponents

Hodell, D. University of Florida, USA; Anselmetti, F. ETH Zürich, Switzerland; Brenner, M. University of Florida, USA.

5.4.2 Overview

A series of sites in Lake Peten-Itza, northern Guatemala was drilled in 2006 to recover sedimentary sequences along a depth transect from ~30 m to near the deepest point (~150 m) in the lake. Six primary and four alternative drilling sites have been identified on the basis of two detailed seismic surveys. A sequence stratigraphic approach was employed to constrain the vertical range of past lake level variations for glacial, interstadial, and interglacial stages during the late Pleistocene. The basal age of the drilled sections is not certain but it is estimated that sequences should span at least the last several glacial-to-interglacial cycles. The sediment archives and pore waters recovered by drilling will be used to test hypotheses related to three broad scientific themes:

- Paleoclimatic history of the northern lowland Neotropics on orbital to suborbital time scales emphasizing marine-terrestrial linkages (e.g., Cariaco Basin, Greenland ice cores, etc.).
- Paleoecology and biogeography of the Maya tropical lowland forest including the history of vegetation change and disturbance by humans, climate change, and fire.
- Biogeochemical cycling in deep lake sediments emphasizing integrated studies of microbiology, geochemistry (interstitial waters), and mineral authigenesis/diagenesis.

5.4.3 Deep Biosphere Component

The main scientific objective in the deep biosphere component is to shed light on biogeochemical cycling in deep lake sediments emphasizing integrated studies of microbiology, geochemistry (interstitial waters), and mineral authigenesis/diagenesis. Geomicrobiology constitutes a strong complementary aspect to the other objectives of the Lake Peten-Itza Drilling Project and will constitute one of the first comprehensive investigations into the microbial ecology and dominant geomicrobiologically mediated processes occurring in deep subsurface lacustrine sediments. This proposed research will complement efforts to characterize the deep marine biosphere program by the Integrated Ocean Drilling Program.

5.5 Eger Rift

5.5.1 Proponents

Spicák, A. Geophysical Institute, Czech Academy of Sciences;
Förster A., Horsfield, B. GFZ Potsdam, Germany.

5.5.2 Overview

An ICDP international workshop was convened to discuss deep drilling in the western part of the Eger Rift area. The Eger Rift, located in the northwestern part of the Bohemian massif, is a world key site that has attracted the international geoscience community for many decades. The rift is the result of young, deep-seated geodynamic processes manifested by episodic Cenozoic volcanism (the youngest at 0.2–0.5 Ma), repeated earthquake swarms, numerous mineral springs, CO_2 emissions with high ^3He content, and abundant mofettes.

One principal scientific objective of drilling the Eger rift is to improve the understanding of triggering mechanisms that generate swarm-earthquake activity. Applying state of the art seismic monitoring technique would allow performing stress field determinations that could be related to in-situ stress field measurements. A 6–7 km deep borehole in western Bohemia would provide a unique possibility to monitor and study the behaviour of rocks and fluids from the surface down to the source region of earthquake swarms.

5.5.3 Deep Biosphere Component

Even more intriguing, and what makes the Eger Rift unique as far as ICDP sites are concerned, is the triggering of deep microbial activity by fluid release during the earthquake swarms (Fig. 8). Methane is generated as part of this activity, attesting to a coupling of the biosphere and geosphere.

Drilling the Eger Rift would provide an exciting opportunity to sample and monitor this fascinating phenomenon.

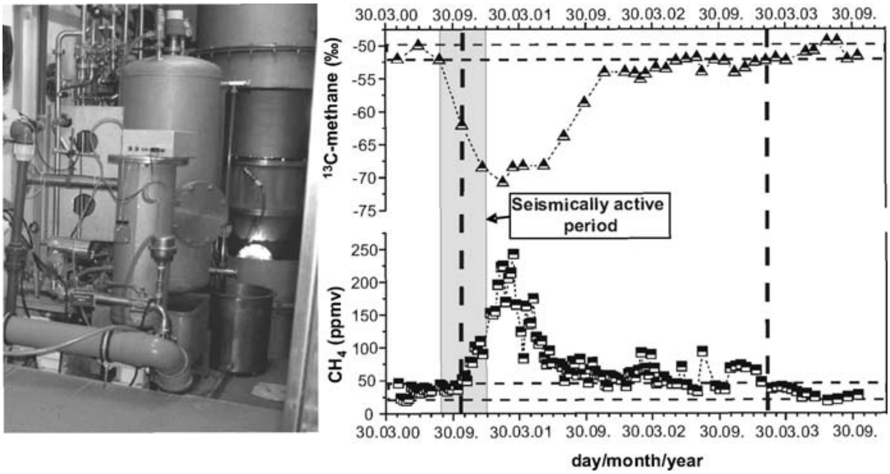

Fig. 8. Photo of the mineral spring “Wettinquelle“ in Bad Brambach (U. Koch, Sächsische Akademie zu Leipzig). Graph visualizing the methane concentration and the carbon isotopic signal of methane detected in the “Wettinquelle“ indicating an increase of methane with a biogenic signature (modified after Bräuer et al. 2005) after an earthquake swarm in the Bad Brambach area. Vertical dashed lines indicate the onset and end of the microbial reaction. Horizontal dashed lines indicate the lower and upper limit of the methane background concentration and its usual carbon isotopic signature.

6 Opportunities and Recommendations

Basically all ICDP drilling targets could be the home for subsurface life. “It seems that life is present wherever a source of energy is present and the limits of life appear to be less restrictive than once assumed” (Kerr 1997). Yet, the Deep Biosphere is elusive, and the task of selecting an “ideal target” is extremely difficult and fraught with risk; the Deep Biosphere remained undetected for so long for good reasons. And then there is the question of contamination; drilling methods, appropriate sampling, sub sampling and monitoring must be regulated and cannot be left to chance.

The way forward is to make sure “Life” is integrated into all levels of ICDP beginning with initial project review by the Scientific Advisory Committee. Technical know-how has to be implemented, from establishing contamination monitoring protocols to the deployment of a mobile geomicrobiology/biogeochemistry laboratory, from collecting samples under in-situ conditions to setting up Deep Biosphere monitoring facilities.

6.1 Science Advisory Group (SAG)

The SAG, the scientific review committee of ICDP, should require proponents to incorporate the element of life into the scientific and technical plan of any given proposal, where appropriate, be that for drilling or a workshop. Because sub-surface microorganisms have been shown to occur in a wide variety of geological settings, almost every ICDP project should have this element built into it. To illustrate the point, major phenomena listed by ICDP as benefiting from drilling, and where microbially mediated processes play a role, are listed below:

- The physical and chemical processes associated with earthquakes and volcanic eruptions (e.g., Eger Rift),
- The manner in which Earth's climate has changed in the recent past and the reasons for such changes (e.g., Peten Itza),
- The effects of major impacts on climate and mass extinctions (e.g., Chesapeake Bay),
- The nature of the Deep Biosphere and its relation to geologic processes such as hydrocarbon maturation, ore deposition and evolution of life on Earth (e.g., Mallik),
- How to safely dispose radioactive and other toxic waste materials.
- How sedimentary basins and hydrocarbon resources originate and evolve (e.g., Mallik),
- How ore deposits are formed in diverse geologic settings.

6.2 Technical Know-How

Detecting indigenous life should be a routine task as far as ICDP drilling is concerned. On-site geomicrobiology and biogeochemistry have to be introduced as routine practice. Furthermore, drilling, sampling and monitoring protocols have to be defined and adopted by ICDP for minimising and recognising contamination. We are already in a good position for doing this.

6.2.1 Conventional Drilling

Most previously described geomicrobiological drilling operations were conducted exclusively as research projects, using dedicated equipment and highly specific and rigorous cleaning protocols (Fredrickson et al. 1995; Boivin-Jahns et al. 1996; Pedersen 1997; Kallmeyer et al. 2005). This approach limits the opportunities for geomicrobiological research because such operations are rather expensive, work intensive and prohibit any collaboration with the industry, as they would be disruptive of the standard working procedures. Future ICDP Geomicrobiology Standards should be defined in a way that they require rather little deviation from standard industrial protocols. As can be seen from previous studies, the efforts should rather be put on quantifying contamination rather than attempting to eliminate it, as even with the most advanced techniques and strictest protocols cannot completely avoid contamination.

6.2.2 On-site Geomicrobiology and Biogeochemistry

In order to make geomicrobiology an integral part of ICDP, it will be necessary to have a dedicated mobile facility for geomicrobiology, which can be sent to any drill site. Standard protocols need to be set up, providing participating scientists around the world with high quality data and samples.

The amount of work on-site should be reduced to an absolute minimum. Only those experiments and analysis should be carried out which cannot be done on preserved samples. However, even by reducing the on-site work to an absolute minimum, a significant workload can be expected, therefore a good working environment is essential. There are many transient parameters, which need to be analyzed on-site to guide microbiological sampling, e.g., redox sensitive pore-water constituents like Fe^{2+}, Mn^{2+}, or volatile compounds such as H_2, CH_4, H_2S. Another major part of on-site work will be the start of enrichment cultures for thermophilic and barophilic organisms.

6.2.3 In-situ Sampling and Cultivation

This technology has been developed, as outlined earlier, and can be readily deployed for ICDP drilling projects

6.3 Monitoring

As part of the Ocean Drilling Program, several boreholes were sealed with CORKs (Circulation Obviation Retrofit Kit). These devices allow researchers to isolate boreholes from the ocean water above the seabed and monitor conditions in the hole for long periods of time. The CORK's data logger can record temperature and pressure data. The data is obtained by a string of sensors that hangs from the CORK to the bottom of the borehole. It also has fittings for recovering samples from inside the hole and allows fluid to be injected into the hole for certain kinds of tests, plus detection of microorganisms (Cowen et al. 2003). The CORK's purpose is to provide a long-term observatory intended to allow a monitored and accessible borehole to return to its pre-drilling state. Similar devices would be highly desirable for ICDP, as they would allow researchers to study subsurface ecosystems for extended periods of time. It would also allow incubating samples under the exact in-situ conditions. There have been some promising pilot studies with in situ cultivation devices in the German KTB Pilot Hole (Stückrad et al. in prep), and with packer devices for sealing off horizontal boreholes in deep Gold mines in South Africa (Baker et al. 2003).

6.4 Potential Drilling Targets

It has already been pointed out that the task of selecting an “ideal target” for Deep Biosphere research is extremely difficult and fraught with risk, especially when the word “deep” refers to thousands, rather than tens or hundreds, of metres below surface. For instance, drilling a deep borehole to determine the maximum temperature at which microbes can live would simply not be feasible because there are too many other factors involved. However, employing the element of “Life” in the drilling strategy of ICDP would yield statistically meaningful results within a relatively short time. For instance, drilling activities in areas of high heat flow versus low heat flow, or high- versus low sedimentation rates would yield valuable information on the journey taken by organic matter as it travels from the surface biosphere into the subsurface, where biosphere-geosphere interactions become more and more important. Potentially, ICDP offers a far broader insight into the workings of the Deep Biosphere because it investigates a more diverse range of geological environments than does IODP.

Some examples of deep biosphere occurrences are presented here to whet the appetite.

6.4.1 Sedimentary Sequences in General

ODP has led the way here with its investigations of deep marine sediments. Numerous studies have proven cell numbers reaching 10^5 to 10^6 cells/cm^3 in several hundreds to one thousand metre depth in marine sequences (e.g., Cragg et al. 1992; Parkes et al. 2000; Reed et al. 2002; Colwell et al. 2004; D’Hondt et al. 2004). The viable or active proportion of microbial cells within those sediments have been determined by microbiological (Cragg et al. 1996; Wellsbury et al. 2002; D’Hondt et al. 2002;

Süß et al. 2004), molecular-microbiological (Schippers et al. 2005), and organic-geochemical methods (Ringelberg et al. 1997; Reed et al. 2002). Microbial diversity based on DNA and RNA analysis have been carried out directly on deep marine sediments (Kormas et al. 2003; Webster et al. 2003; Newberry et al. 2004) or on cultures grown from the sediment community (Bale et al. 1997; Toffin et al. 2004, 2005). Bacteria and archaea, some of them show close similarity to microorganisms in other or deep-sea environments, and others representing novel species have been described. It is important to note that the vast majority of clones to date still remain unidentified. The first ODP Leg with an exclusive "deep biosphere" focus, Leg 201, sailed in February-March 2002. All sites of ODP Leg 201 were low temperature sites, reaching a maximum temperature of only 25°C (D'Hondt et al. 2004). This is the preferential range for psychrophilic and mesophilic microorganisms, which seem to exceed the amounts of archaea for the investigated sites (Schippers et al. 2005). An alternative and complementary insight into the composition of these microbial communities is revealed by molecular "life markers" of viable microbes, i.e., intact phospholipids (PL), detected in deep subsurface sediments (Zink et al. 2003; Sturt et al. 2004). They were initially detected in sediments of the Nankai Trough (ODP Leg 190) (Zink et al. 2003) at temperatures up to 84°C, where incipient petroleum generation was also underway, and possibly providing carbon sources for the organisms (Horsfield et al. 2006).

As far as the terrestrial biosphere is concerned, the feeding of deep subsurface microbes by diagenetic formation of organic compounds is at the focus of the DEBITS (Deep Biosphere In Terrestrial Systems) borehole in New Zealand, where peats and lignites are viewed as "feeders" and sands as "carriers" for a microbial ecosystem (Horsfield et al. in prep). First results show that an active and abundant microbial inventory is present (Fig. 9). Early fundamental studies on the terrestrial deep biosphere focussed on mostly aerobic microbial communities within aquifers, and included environmental considerations (Balkwill et al. 1989; Jimenez 1990; Zlatkin et al. 1996). Lehman et al. (1995) were able to distinguish different microbial communities in drill mud, surface soil, inner and outer cores from the Thorn Hill well (Virginia, USA), and thus to determine the degree of microbial contamination. Colwell et al. (1997) identified bacteria in deep sediment cores from the Piceance Basin (Colorado, USA) down to a depth of 862 m and the temperature range 43 to 85°C. As part of a remediation study, Chandler et al. (1998) sampled a low-biomass paleosol in 188 m depth with extremely low metabolic activity and were able to detect a high variety of bacterial and archaeal clones applying molecular-microbiological methods.

6.4.2 Aquifers

Groundwater aquifers were among the first subsurface environments to be studied microbiologically. Few studies were conducted until the 1980s, when researchers in the U.S. and Europe began testing groundwater pumped from wells for the presence of microorganisms (Hirsch and Rades-Rohkohl 1983) and collecting cores from shallow aquifers (<10 m). Ghiorse and Balkwill (1983) and Wilson et al. (1983) collected cores from shallow aquifers in Oklahoma and Louisiana, respectively, and found surprisingly high numbers of microbes (up to 10^7 bacteria g^{-1} by direct microscopic counts) and a diversity of morphological and metabolic types. These early findings stimulated interest in much deeper aquifers. The Atlantic Coastal Plain aquifers became the focus of intense study by U.S. Department of Energy (DOE)-funded researchers as well as by researchers of the U.S. Geological Survey. The DOE-funded project collected cores from four boreholes drilled to depths of nearly 500 m in the vicinity of the Savannah River Site in South Carolina. Samples were collected at various depths from various aquifers and intervening aquitards. Conventional wisdom at the time contended that numbers of microorganisms would decline quickly with depth (extrapolating from soil profile data) and thus that few if any microbes would be found below a few meters depth. Contrary to these firmly held beliefs, many of the deep groundwater aquifers showed direct counts of microorganisms of approximately 10^7 cells g^{-1} and culturable counts that were nearly as high (10^6 CFU g^{-1}) (Balkwill 1989; Balkwill et al. 1989). The communities of microorganisms in these aquifer sediments were also found to be phylogenetically and metabolically diverse (Balkwill 1989; Balkwill et al. 1989; Fredrickson et al. 1989). The fine-textured aquitard sediments showed considerably fewer microbes, but were far from sterile (~10^3 cells g^{-1}).

Besides being present and viable, these microbes were also found to be metabolically active and strongly, albeit slowly, influencing the groundwater chemistry of their environments. The four boreholes were spaced several km apart and intercepted the aquifers at points along flow paths at different distances from the recharge zone. The deepest of the aquifers, the Middendorf, was of particular interest. Murphy et al. (1992) found that the groundwater age and chemistry changed along the flow path. The age of the groundwater sampled at the most distal hole was 10,500 years. The chemistry changes along the flow path indicated a sequential depletion of electron acceptors, beginning with O_2 and proceeding through nitrate, Fe^{3+}, and sulfate. Methanogenesis was the dominant electron accepting process in the oldest, most distal sample. This depletion of electron acceptors proceeds over 10s of km and thousands of years due to the low concentration and low quality of organic carbon as electron donor for microbial metabolism. Though relatively low in numbers, the microbes in aquitard sediments transform buried organic matter into fermentation end-products that diffuse into the aquitards (McMahon and Chapelle 1991b). The slow changes in groundwater chemistry along the flow path were used to estimate rates of microbial activity, which were found to be orders of magnitude slower than in surface environments (Chapelle and Lovley 1990; Phelps et al. 1994; Kieft and Phelps 1997). Phelps et al. (1994) further estimated the microbial generation times in subsurface aquifers to be hundreds or thousands of years.

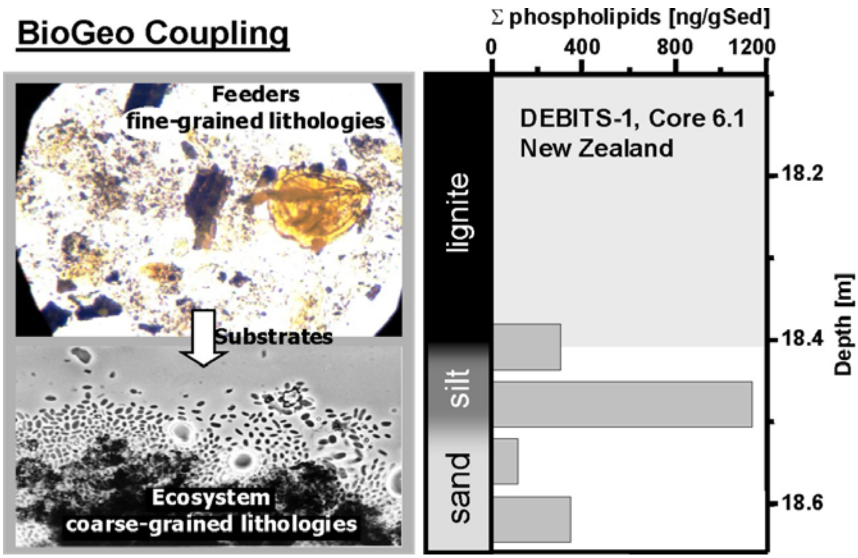

Fig. 9. Biosphere-Geosphere interaction of organic carbon rich „feeder“ lithologies and coarser-grained „carrier“ lithologies. Diagram of intact phospholipids, acting as indicators for the occurrence of microbial life, relative to different lithologies in the DEBITS-1, Core 6.1 drilled during the DEBITS (Deep Biosphere In Terrestrial Systems) project in New Zealand. The phospholipid concentrations indicate an increase of microbial life in the coarser grained sediments adjacent to the organic carbon rich “feeder“ sediments.

The importance of these findings cannot be overemphasized. The discovery of diverse, metabolically active microbial ecosystems in deep aquifers extended our knowledge of the terrestrial biosphere to previously unimagined depths and inspired drilling and coring efforts at other sites and in other types of subsurface environments, some of which are discussed below. These discoveries were made possible by the development of novel methods for drilling and coring to obtain pristine samples representative of the deep subsurface. The study of microbes in aquifers is far from complete. Relatively few groundwater aquifers have been examined for their biogeochemistry and some of those that have received the most intense study, e.g., the U. S. Atlantic Coastal Plain sedimentary aquifers, are relatively simple. The importance of deep groundwater aquifers as a source of potable water and their importance to biogeochemical cycling suggest that they be targeted for deep drilling, sampling, and microbiological characterization.

6.4.3 Vadose Zone Environments

The vadose zone extends from the soil surface to the underlying water table, a distance that may be a meter or two in areas of high precipitation or hundreds of meters in extremely arid regions. Studies in the arid western U.S. have shown that vadose zone rocks and sediments harbor microorganisms in relatively low numbers and with relatively low rates of metabolic activities. While groundwater aquifers can have high numbers of microbes due to the high rates of groundwater flow and thus nutrient flux (relative to other subsurface environments), vadose zone is relatively static, with groundwater flow being dominated by diffusion. Microbes exist in vadose zone environments within thin water films on solid surfaces and also at air-water interfaces (Wan et al. 1994). Unless they are attached to buried organic matter, they generally exist in microzones of depleted nutrients and are thus in a starved state. Despite the challenging conditions, viable microbes exist in deep arid vadose zones, albeit in low numbers (Brockman et al. 1992; Kieft et al. 1993; Fredrickson et al. 1994; Kieft et al. 1997; Kieft et al. 1998). In some cases, they extend our knowledge of long-term microbial starvation survival (anabiosis) and they are of practical importance for the siting and long-term performance of radioactive waste repositories (Kieft et al. 1997) and for bioremediation of contaminated vadose zones.

6.4.4 Deep Fractured Rock

Fractured rock environments are considerably more difficult to sample than sedimentary environments. Colwell et al. (1992) devised novel techniques for coring in deep basalt rock for microbiology. These fractured rock environments were found to contain viable, functioning microbial communities. Stevens et al. (1993) found a diversity of anaerobic microbes, including sulfate reducers and methanogens in deep basalt aquifers and later showed that methanogens in some of these basaltic environments gain their energy from H_2 that is generated by rock-water interaction (Stevens and McKinley 1995). The finding of subsurface microbial ecosystems metabolizing energy sources derived not from photosynthesis but instead from purely geochemical processes has remained controversial; nonetheless, it has been demonstrated in another deep, fractured basalt environment (Chapelle et al. 2002). K. Pedersen has performed extensive studies in deep fractured granite in Sweden and also reported that microbes are functioning on gaseous energy sources, termed "geogas", produced from the interactions of rock and water (Pedersen 1997). More recently, studies conducted in deep gold mines in South Africa have shown the presence of a diversity of microbes in deep (~3 km) fractured rock, including moderately thermophilic anaerobic microorganisms, and that some of these microbes are gaining their energy from gaseous energy from H_2, methane, and other short-chain hydrocarbons generated by the radiolysis of water and by rock-water reactions (Takai et al. 2001a,b; Moser et al. 2003; Onstott et al. 2003; Ward et al. 2004; Lin et al. 2005a,b).

6.4.5 Permafrost Environments

In polar regions permafrost covers more than 25% of the land surface (Zhang et al. 1999), and can extend to several hundreds of meters depth (e.g., 600 – 800 m in East Siberia). During the relatively short period of Arctic/Antarctic summer only the surface zones (active layer) of permafrost sediments thaws. Permafrost can be cemented by ice which is typical for the Arctic regions, or, in the case of insufficient interstitial water, may be dry like the Antarctic polar deserts. Permafrost can be divided into three temperature depth zones which characterize typical living conditions for microorganisms: (i) The active layer with an extreme temperature regime from about +15 to –35° C, (ii) the correlated upper, perennially frozen permafrost sediments (1-20 m thickness) with smaller seasonal temperature variation of about 0 to –15° C above the zero annual amplitude (French 1996) and (iii) the deeper permafrost sediments which are characterized by a stable temperature regime of about –5 to –10°C.

The soils of the active layer and upper permafrost sediments are an area of active physico-chemical processes under extreme conditions (Fiedler et al. 2004), in which a diverse range of microorganisms have been discovered (Wagner et al. 2005). The deep permafrost sediments are characterized by a very stable environment where microbes can both adapt to temperature far below zero and survive for millions of years (Vorobyova et al. 1997). In Holocene and Late Pleistocene permafrost deposits from the Lena Delta (Siberia) for instance a similar diversity of microorganisms was detected by phospholipid biomarkers and DNA analysis compared to the upper active layer of the frozen ground (Wagner and Gattinger 2004; Jurgens 2005).

Furthermore, the degradation of permafrost and the associated release of climate relevant trace gases from intensified turnover of organic carbon and from destabilised gas hydrates represent a potential environmental hazard. One third of the global carbon pool is stored in northern latitudes (Post et al. 1982), so there is considerable interest in predicting how the carbon balance of northern ecosystem will respond to climate change. Permafrost soils represent already a significant source for the climate-relevant trace gas methane (Wagner et al. 2003; Kutzbach et al. 2004). However, the permafrost microbial community has been described as a *community of survivors,* which have overcome the combined action of extremely cold temperature, freeze-thawing cycles, desiccation and starvation (Gilichinsky and Wagener 1995). There are only a few studies on microbial diversity (structure and function) in permafrost environments, indicating the need for a comprehensive inventory of these habitats.

6.4.6 Biogenic Gas Reservoirs

Biogenic gas, with its characteristically light carbon isotopic signature, occurs down to 3 km depth (Schoell 1980). Methanogenic microorganisms occur widespread in the deep subterranean biosphere (for review see Kotelnikova 2002), but little is known about these organisms, nor about the maximum depth to which methanogenesis takes place.

Two main metabolic pathways for the generation of methane are known (Whiticar et al. 1986; Kotelnikova 2002). Autotrophic methanogens may use different electron donors for carbon dioxide reduction. Hydrogen which has been detected in highly variable concentrations in different subsurface environments appears to be an important electron donor. The second pathway is that used by acetoclastic methanogens which disproportionate the widespread organic acid acetate to methane and carbon dioxide. Stable isotope signatures appear to indicate that carbon dioxide reduction plays the more important role (Kotelnikova 2002). A third mechanism, revealed in recent years, involves the biodegradation within oil reservoirs or coal seams (Zengler et al. 1999; Anderson and Lovley 2000; Townsend et al. 2003; Head et al. 2003). Biodegraded reservoirs often contain only little carbon dioxide but high concentrations of methane, and with an oil rim (Larter and di Primio 2005). Economic accumulations of biogenic methane may occur in shallow organic-rich shales, such as the Antrim shale, Michigan Basin, which is viewed as self-sourcing (Martini et al. 1996). Similarly, coalbed methane has been shown to be of microbial or mixed origin (Smith and Pallasser 1996; Thielemann et al. 2004). It has been suggested that biodegradation of coal components may produce carbon dioxide which then is reduced to methane. Based on parallels with gas hydrates (see below), it can be anticipated that methanotrophy plays a role in subterranean gas reservoirs.

6.4.7 Terrestrial Gas Hydrates

Gas hydrates form when high concentrations of mainly methane (biogenic or thermogenic) and water combine in subsurface strata under specific conditions of low temperature and high pressure to form clathrates (Kvenvolden 1988; Kennicutt et al. 1993). As far as continental environments are concerned, their occurrence is restricted to polar regions, such as the Mackenzie Delta, Alaska and northern Siberia (Kvenvolden and Lorenson 2001). Here, the shallowest occurrence of gas hydrates is about 150 m below the surface, and the deepest typically less than 1000 m below the continental surface. Actual limits are defined by the regional geothermal gradient. Little is known about the microbial communities associated with terrestrial gas hydrates; much more information is available on marine gas hydrates in the deep sea along continental margins. While the clathrated gas in the terrestrial deep sediments of the Mallik 2L-38 well Mackenzie Delta, Northern Canada is of thermal origin, Colwell et al. (1999) reported the existence of methanogenic microbial communities in juxtaposed sediments. Life markers were detected in the nearby Mallik 5L-38 gas hydrate production research well, pointing to the occurrence of a viable deep microbial community (Mangelsdorf et al. 2005). While the aerobic decomposition of methane by methanotrophic microorganisms within the active layer of permafrost surface sediments is a common known process (Wagner et al. 2003), it is not yet known whether anaerobic oxidation of methane takes place within terrestrial gas hydrate bearing sediments. This is relevant when considering the escape of greenhouse gases into the atmosphere. The question whether microbes consume methane directly from gas hydrates is currently still uncertain (Valentine 2002). From studies in marine environments it is assumed that the anaerobic oxidation of methane occurs in the vicinity of gas hydrate deposits actuated by the dissolved methane in the pore water which is in equilibrium with the gas hydrates (Valentine 2002; Wellsbury and Parkes 2000).

6.4.8 Biodegraded Petroleum Reservoirs

Biodegradation of crude oil leads to increased contents of organic acids, sulphur and metals and as a consequence, biodegraded petroleum is of lower economic value. The changes in bulk composition attributed to petroleum biodegradation are reflected by systematic alteration at the molecular level. Different types of petroleum constituents are removed at different rates, a phenomenon which is used in empirical schemes for classifying crude oil and natural gas according to biodegradation level (Peters and Moldowan 1993; Wenger et al. 2001). Biodegradation is normally observed only in relatively shallow reservoirs at temperatures below 80° C. The reason for this temperature limit is not completely understood since hyperthermophilic microorganisms have been isolated from oil field formation waters (Stetter et al. 1993). However, up until now there is no conclusive evidence for hyperthermophilic microorganisms oxidising hydrocarbons. It has been suggested that deep burial sterilisation of reservoir formations might prevent biodegradation of hydrocarbons in uplifted reservoirs (Wilhelms et al. 2001). While other factors such as pressure, salinity or pH are highly variable in petroleum reservoirs, they do not appear to exclude or promote microbial life principally (Magot et al. 2000). Almost nothing is known about hydrocarbon-degrading microorganisms from these habitats, though degradation pathways have been elucidated (Widdel and Rabus 2001; Wilkes et al. 2002). What is clear is that the biodegradation of hydrocarbons is very slow, and the supply of electron acceptors and nutrients appears to be another crucial factor. Significant accumulations of hydrocarbons are only feasible if biodegradation rates are slower than filling rates of the reservoirs (Larter et al. 2003). Not much is known about the availability of macro- and micronutrients. Estimated water-oil-volume ratios in most cases are too low for a sufficient supply of electron acceptors. Volumetrically significant aerobic biodegradation of petroleum in reservoirs is very unlikely; anaerobic degradation is the principal route.

7 Concluding Remarks

The Ocean Drilling Program (ODP) carried out the first studies that demonstrated that an abundance of microorganisms exists at depths to 750 m in marine sediments. When the Integrated Ocean Drilling Program replaced the ODP, they selected studies of the deep seafloor biosphere as one of their major research initiatives (www.iodp.org). Their Initial Science Plan calls for each major scientific drilling project to include a biosphere component, with some voyages having the investigation of an aspect of the deep biosphere as the central rationale. This visionary policy has led to a flourishing of deep marine science, with significant findings published in high-profile journals (e.g., Cowen et al. 2003; D'Hondt et al. 2004; Kelley et al. 2005; Schippers et al. 2005, Parkes et al. 2005). The IODP's embracing of deep biosphere studies as an essential component of interdisciplinary investigations of the deep subsurface has enriched the overall scientific effort rather than subtracting from the resources for investigators in other disciplines. IODP simply does not drill to the depths required to test the temperature, pressure, salinity, and porosity limits of the deep biosphere. Nor do they probe a broad enough range of geological environments and ages to address the geodynamics of sedimentary systems; it is the latter which controls *inter alia* the mass fluxes that are of paramount importance to life in the subsurface. ICDP now has a unique opportunity to be the key global organization to foster research on the deep biosphere. It offers the geological diversity needed to research into what makes the deep biosphere tick. The organisation can dictate the way forward by providing not only funds but also the practical means (directives for including the element "life", sampling protocols, mobile laboratory) for going forward. We are not talking simply about advances in science, important as they are; the benefits of understanding the influence of microbes on deep aquifers, potential nuclear waste disposal sites, and their effects on the composition and ultimate recovery of hydrocarbon resources and other mineral deposits are all of significant value to society.

We should not underestimate the value of partnerships with industry. Petroleum companies are not motivated to properly handle samples for deep biosphere studies by themselves, but the question arises as to whether it is practicable to "piggyback" on drilling operations *using ICDP funding* in some circumstances. "Putting any kind of tool down the hole would be resisted because of fears of losing the hole. If it involved running a tool along with a regular planned log run, then this might be OK. If it involved taking sterile core of an interval they already plan to core, that might work as well. Anything that involves extra "rig time" is very expensive (ca. $100,000 per day), so ICDP would have to cover that. Piggybacking on a development well might be easier, because it probably involves less mechanical/drilling risk as they would have drilled the interval in the area many times " (Franks, personal communication).

Working together with industry should not be ruled out; indeed this should be explored on a case-by-case basis because extra rig time is still a cheap option compared to total rig time in the case of deep holes.

Finally, we look forward to a new decade of drilling the deep biosphere, with all the technical and organisational challenges it presents. Let's see what surprises are in store!

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Active Volcanic Systems

John C. Eichelberger[1] and Kozo Uto[2]

[1]Geophysical Institute, University of Alaska Fairbanks, AK 99775, U.S.A.
e-mail: eich@gi.alaska.edu (corresponding author)

[2]National Institute of Advanced Industrial Science and Technology, 1-3-1 Kasumigaseki, Chiyoda-ku, Tokyo 100-8921, Japan

Abstract

Drilling into volcanic systems has already yielded important results concerning the structure and history of volcanic systems, and the transport of magma and heat within them. These lines of investigation should be continued so that all common kinds of volcanic systems are explored. Although the engineering and safety challenges are large, the ultimate scientific goal, with potential geothermal energy and hazard mitigation benefits, is to cross the solidus frontier into magma.

1 Importance of Volcanism

Volcanism is a fundamental aspect of all terrestrial planets and some satellites in the solar system. Production and upward migration of melts occur when heat generation exceeds that which can be dissipated by conduction, and result in the development of crust and atmosphere, and in the cases of Earth and ancient Mars, the hydrosphere. A feature that may be unique to Earth is the bimodal character of its crust. Beneath the oceans lies thin, young, continuously basaltic crust that is continuously being generated and destroyed. The continents are thicker; substantially granitic, a lithology virtually absent in ocean crust; and their formation appears to be irreversible. Thus it is ironic that we now understand much more about the origin of oceans than about the origin of the continents on which we live. This is, because we do not understand why some volcanic systems develop silicic plutons that can resist subduction and add to continental crust, whereas others do not. This, in turn, is because we really do not understand how magma behaves within the crust, an environment where it loses heat to its surroundings and mass to eruption. Drilling is an important tool for understanding how magma behaves, physically and chemically, in Earth's crust. Drilling helps to reveal the record of magmatic evolution, and allows the exploration of structures and conditions formed by migration of magma.

Volcanism is of immediate concern to humankind. Foremost is the hazard from volcanic eruptions. The danger to human population is growing, for example the cities of Tokyo, Japan, near Mount Fuji, and of Naples, Italy, area near Campi Flegrei and Vesuvius (Fig. 1). In addition, reliance on jet aircraft for long-distance travel places travelers at lethal risk from volcanic ash clouds (Miller and Casadevall 2000), particularly in the circum-Pacific region, where air routes traverse highly active volcanic arcs. Because eruptions of monitored volcanoes can now be forecast with some reliability, an alliance between scientists and governments can minimize damage to infrastructure, loss of livelihood, and loss of life through appropriate protective measures and, when necessary, evacuations. To the extent that it can be shown that drilling into volcanic systems can substantially improve predictive capabilities, either at specific sites or in general through improved understanding of relevant processes, then the expenditure of millions of dollars for such drilling is a wise investment.

The scale of volcanic hazard ranges from local tragedy to global catastrophe. The debate of the last quarter century about whether or not impact events or huge volcanic eruptions caused mass extinctions by creating a "nuclear winter" serves to highlight the global threat of great eruptions. For example, Tambora in 1815 is thought to have caused the world's last great famine (see review by Oppenheimer 2003).

Volcanic systems also represent a vast and largely untapped resource beneath our feet. With the global economy passing the projected peak in oil production, alternative forms of energy such as geothermal are urgently needed. The recent rise in oil prices has spurred a number of ambitious projects, both into traditional hydrothermal systems and the humanly manipulated hot-dry-rock regime. There is an evident disconnect between the scientific community and the commercial sector here, with a need for scientists to show greater interest in partnering with industry. Geothermal energy will not be a complete solution to the global economy's demand for energy, but it will be key in areas where the crust is hot and other energy sources distant.

There is also the issue of economically important deposits of metals. Except in the case of impact structures, many of these are precipitates from hydrothermal fluids, often associated with volcanic systems (e.g., Elders and Sass 1988). In some cases, the metals themselves are derived from magmas, exhaled and then concentrated in the associated hydrothermal environment.

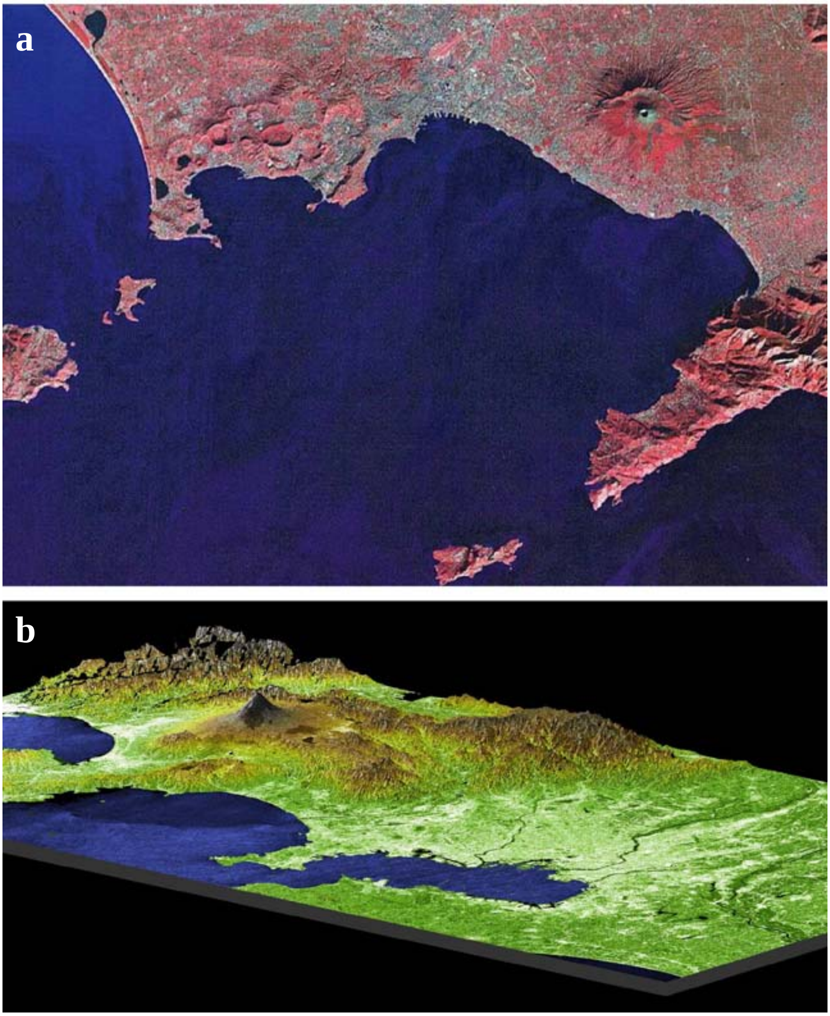

Fig. 1. a. Campi Flegrei (upper left) and Vesuvius (upper right) in the heavily urbanized Naples area, Italy. Landsat image (USGS). North is up and width of view is 55 km. **b.** Dense urbanization of the Tokyo and Yokohama areas near Mount Fuji (Landsat draped on Space Shuttle synthetic aperture radar DEM, NASA), looking obliquely southwestward. Width of view is approximately 200 km.

Volcanism is also of concern in the long-term isolation of radioactive waste. Waste isolation is already a first order problem for our civilization, but it may become much more so, as nuclear energy is an obvious solution to our CO_2 and SO_2 emissions problem arising from reliance on fossil fuels. There is general agreement that the solution to waste isolation is deep burial and that the time frame for isolation must be very long, long compared to not just civilization but to the existence of advanced humanoids. In the case of the planned waste repository in the Southwest Nevada Volcanic Field (U.S.A.), what are the risks of magmatic incursion into the waste repository (Ho and Smith 1988)? This question is being investigated by drilling the relatively young volcanoes there. For countries such as Japan, located above a subduction zone, it is critical to choose repository sites to avoid future volcanic eruptions. Otherwise, highly radioactive dust might be spread over the world by a volcanic plume rising up to the stratosphere.

2 The Role of Drilling

Fossil volcanic and hydrothermal systems are well exposed in the geologic record. Much has been and is being learned from study of surface exposures. These provide rich three-dimensional information, although more than 1000 m of vertical exposure within a single magma plumbing system is extremely rare. Likewise, geophysical “remote sensing” of active systems from the surface is important. For example, earthquake distribution may define the brittle/ductile transition and hence an isothermal surface surrounding a magma body (e.g., Pallister et al. 1992). Measurement of surface deformation can constrain the position and shape of a magma body and provide a measure of the rate it is filling or expelling magma. Inference can be made concerning conditions of storage of magma from petrological analysis of eruption products, from laboratory replication of magma storage and ascent conditions, and to a limited extent from gas emissions (e.g., Rutherford and Devine 2003; Wallace and Gerlach 1994). The dynamics of magma ascent are amenable to computational modeling, although the thermal, chemical, and mechanical processes have yet to be satisfactorily coupled.

None of these indirect approaches provide a substitute for what could be gained from direct observation of volcanoes by drilling: geometry and structure of a system for which eruptive behavior is known, and physical and chemical conditions within volcanic systems at known points of time before, during and after volcanic events.

From the standpoint of volcanic hazards, there are at least two practical benefits from drilling:

1. “Ground truth” for volcano monitoring: Various surface observations are conducted to monitor movement of magma beneath and inside volcanoes for the prediction of volcanic eruptions. Models are constructed to understand the magmatic behavior from such observations.

Such models can only be verified by direct observations through drilling into volcanic structures. This is important for making more accurate and appropriate predictions of future volcanic eruptions.

2. Volcano stratigraphy: Some active volcanoes have very long times of repose between eruptions, on the order of 10^3 to 10^5 years, and historical records and even surface exposure of geologic records are, therefore, in some cases insufficient for the assessment of possible future eruptions. Understanding the complete eruptive history of active volcanoes is essential for the mid- to long-term forecast of future volcanic eruptions to reduce the volcanic risks, construct appropriate evacuation plans, and manage future population growth. Drilling into the flanks of volcanic edifices, where significant human populations are at risk, can add significantly to studies of surface deposits in unveiling evidence of volcanic disasters in the past. This is especially true for caldera systems. Most caldera volcanoes have experienced multiple collapse events and may collapse again in the future. Caldera formation is catastrophic and generates large depressions that later fill with more eruptive material, with deposits accessible only by drilling. The lakes, hot springs, and flat fertile land that characterize intracaldera landscapes often attract large human populations. Significant eruptions would cause tremendous hazards in and around the caldera. Some of these systems are in a nearly continuous state of unrest, that at normal volcanoes would presage an eruption. Apparently magmatic flux of melts or volatiles may be resupplied to a large active magma chamber that is able to absorb these inputs without eruption, but with accompanying earthquake swarms and/or ground deformations that cause civil crises (e.g., Long Valley Caldera: Hill et al. 2003; Campi Flegrei, de Natale et al. 2000). Drilling to unveil caldera fill stratigraphy, as well as tracking active magmatic processes through instruments emplaced at depth in boreholes, are important to evaluating when unrest reflects an imminent eruption and when it is not cause for alarm.

3 History of Drilling of Active Volcanic Systems

Serious scientific drilling of magmatic systems began with drilling through the crust of Kilauea Iki lava lake in the 1970s. This remarkable work set temperature records that still stand, and succeeded in recording both the mechanism and rate of coupled conductive and convective cooling, as well as defining the liquid line of descent from basalt to rhyolite in basaltic magma (Hardee et al. 1981; Helz and Thornber 1987). Following the same spirit of drilling very young exemplary systems, drilling of Inyo Domes in California intersected the conduit and feeder dike of a 600-year-old rhyolite eruption (Eichelberger et al. 1986). The system was found to be disappointingly (but not surprisingly) cold, but results from analysis of core led to development of the permeable foam model of silicic magma degassing. The Unzen Scientific Drilling Project (USDP) carried this further, into the subsurface of a system that had just completed a carefully monitored 4-year eruption episode and was still hot. In an impressive exercise of geophysical targeting and directional drilling techniques, the conduit was penetrated and sampled only 9 years after the eruption ended (Fig. 2; Nakada et al. 2005). Surprisingly, the conduit had cooled to below 200^{o}C, so no new thermal frontier was crossed. However, important results on physical configuration of the system and behavior of magma at depth during eruption and after emplacement are being obtained. The center of the volcano was revealed to comprise a broad conduit zone of intense brecciation and diking. The low temperature of the youngest dike is a testament to the efficacy of hydrothermal cooling of igneous intrusions, and important in considering initial conditions during ascent of magmas and initiation of eruptions. Unless eruptions are frequent, volcanic systems develop a strong, cold “lid”, and perhaps this is why the precursory phase of the Unzen eruption lasted 18 months before magma appeared at the surface.

Another attempt to penetrate the near-magmatic environment was drilling into the actively inflating resurgent dome of Long Valley Caldera. This drilling too yielded surprisingly low temperatures, only 100^{o}C at 3 km (Sorey et al. 2000), a temperature somewhat below average for the Basin and Range Province of interior western US at similar depths. This result re-enforced growing evidence from seismic tomography studies that the caldera is not currently underlain by a huge, shallow magma chamber such as the one that was thought to exist just prior to the caldera-forming eruption 760,000 years ago (Bailey et al. 1976). Indeed, the region had been viewed as one of the most likely places in the world to find a large, mostly liquid magma reservoir. Although the structural relief of the dome had been interpreted as a consequence of the influx of new magma into the central magma body following caldera collapse in the traditional model for large, resurgent calderas by Smith and Bailey (1966), drilling revealed that sills within the intracaldera tuff are of sufficient thickness to account for this structure (McConnell et al. 1995). Thus, drilling results have tended to strengthen a new trend of thought in igneous geology and petrology, in which the importance or even existence of large mostly liquid magma bodies is being questioned (e.g., Glazner et al. 2004; Eichelberger et al. 2006).

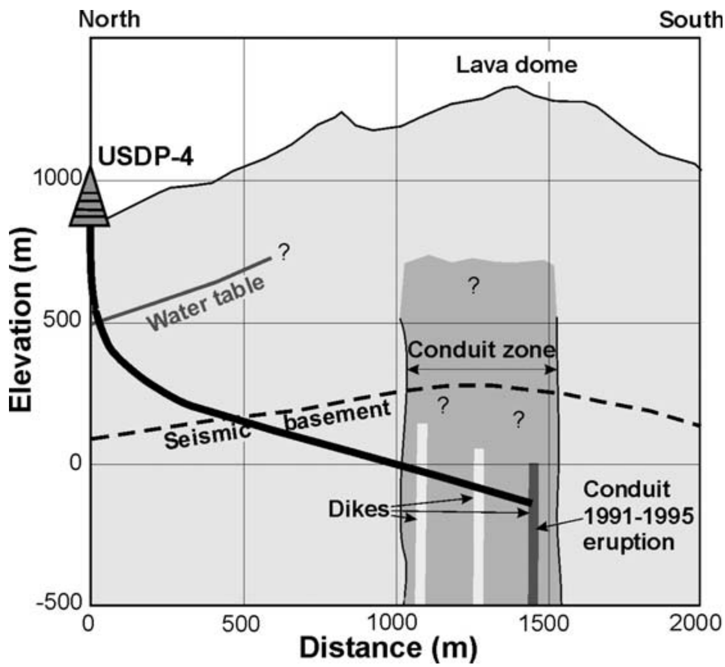

Fig. 2. The ICDP drilling at Mt. Unzen, Japan, was the first penetration and sampling of the hot conduit of an active volcano. The modern conduit occurs within a broad zone of brecciation and older conduits. It has undergone phenocryst resorption, alteration, and decomposition, carbonate and pyrite addition, and rapid cooling since emplacement 9 years prior to drilling (after Nakada et al. 2005).

Another important line of investigation might be termed *volcano stratigraphy*, an objective of the first phase of drilling at Unzen as well as the primary objective of deep drilling of the Hawaiian Scientific Drilling Project (HSDP). Flank holes at Unzen recorded a remarkably monotonous output of hybrid, low explosivity lava effusions over a half-million-year period, the onset of which was synchronous with initiation of subsidence of a graben in which the volcano is situated (Fig. 3; Hoshizumi et al. 1999). It is likely that the hybrid characteristics of magmatic output and the graben structure of the volcanic setting reflect establishment of a modest-volume, crystal-rich silicic magma chamber in the mid crust, although the chemical invariance of mixed output thus far defies explanation. Drilling at Hilo, Hawaii has revealed new aspects of shield volcano structure, recorded the interplay between edifice construction and crustal subsidence under the growing load, and provided a volcanic sample transect across Earth’s largest mantle plume (DePaolo and Stolper 1996).

Drilling directly into volcanoes is motivated by scientific objectives, but drilling into hydrothermal systems more often has the economic objective of geothermal energy extraction. As a result, hydrothermal targets have received much more exploration than more purely magmatic ones. However, scientific drilling has worked to extend conventional geothermal drilling into new thermal regimes. Such efforts include the deepening of a Salton Sea borehole in the 80s to reach highly concentrated brines (Elders and Sass 1988). Most spectacularly, a 4-km borehole in the Kakkonda geothermal field of Iwate Prefecture, Japan penetrated the conductive margin of a “zero-age” granite, reaching a formation temperature well in excess of 500°C (Saito et al. 1998).

A good example of the how commercial geothermal exploration can yield results important to volcanology is Nigorikawa Caldera in Southern Hokkaido, Japan. This small funnel-shaped caldera is about 3 km in diameter and formed about 12000 years ago (Fig. 4; Hanano 2005). This young, yet almost hidden, caldera in the Mori Geothermal Field and its subsurface structure have been revealed by commercial geothermal wells extending down to 3 km beneath the surface. The caldera is filled with fall-back deposits invaded by intrusives, and narrows to a diatreme pipe of a few hundred meters diameter at depth. Many of these insights from geothermal drilling into volcanic systems have yet to be incorporated in volcanological models, perhaps because drilling results or potential results are simply outside the mindset of the volcanological community. We assert that such a view must change if we are to make fundamental advances in this field.

4 Safety and Permitting

It should be noted that scientific drilling in volcanic regimes entails special challenges of safe operation and permitting. These are easiest to deal with in established geothermal fields, where many boreholes have already been permitted and drilled, subsurface conditions are known, and the objective is to incrementally push the frontier. Where no boreholes have previously been drilled, conditions are subject to speculation and so a drilling design for the “worst-case” may have to be adopted. Such a project may also be seen as legally precedent-setting, and, therefore, permitting becomes a problem.

In the most challenging case of active volcanoes, there are often special legal restrictions to access due to park or wilderness status or hazards. There is also the understandable public concern that drilling might trigger an eruption. In the case of Unzen, these problems were overcome through careful negotiations with appropriate government agencies and through many public meetings. Problems were resolved by selecting a site outside the central protected area, but this entailed the added expenses of a longer borehole and building an access road. In the case of the Katmai Scientific Drilling Project proposed in the 1980s, negotiations with the government land-managing agency did not reach a successful conclusion despite a lengthy and expensive permitting process (Eichelberger and Sattler 1994) because of legal concerns over wilderness status of the site. The project had to be abandoned. Regulations that control the award of permits have become more severe with time, so that some past projects such as drilling at Kilauea Iki lava lake in Hawaiian Volcanoes National Park, Inyo Domes in Inyo National Forest, and the hydrothermal system in Yellowstone National Park might not be possible today. Indeed, a compelling case for mitigating volcanic hazards is just as important for obtaining the necessary permits for drilling as it is for obtaining funding. A science argument may not be enough.

To allay concerns about triggering eruption, it would be useful to model the consequences of a borehole penetrating an active magma body. This is well within the capabilities of the volcanological community. At least for viscous, silicic magma, it should be expected that flow through a narrow borehole is impossible, and that the main problem might be escape of magmatic gas, which should be controllable in the same way that hydrothermal fluids are controllable: through cooling and maintenance of borehole pressure. Such seemingly specialized modeling might not seem appealing to magma dynamicists, but actually it is an adaptation of the problem of groundwater contacting magma through a fracture. Likewise, questions of borehole stability are analogous to the question of conduit stability during an explosive eruption, wherein the conduit will be underpressured above the level of magma fragmentation (Mastin and Ghiorso 2000). This important issue has yet to be incorporated into even the most advanced eruption models (e.g., Mason et al. 2006). Rather, conduit walls are assumed to have infinite strength.

5 Targets for the Future

Certain classes of targets, given below, stand out as most appropriate for scientific drilling in volcanic systems. Generally, they represent continuation of themes already begun. However, the remarkable progress in geophysical imaging of the sub-surface (useful for targeting drilling but will never achieve the resolution needed to understand local scale diffusive processes), and in high-temperature drilling, logging technology, and directional drilling (with high spatial resolution), ensure that the next ten years will deliver exciting new results.

5.1 The Volcanic Edifice

The simplest, but one of the richest, topics for scientific drilling is volcanic stratigraphy: the record of eruption history from continuous core extending from the surface to the base of a large volcanic edifice (Fig. 3). Such drilling provides a time series of magma composition and eruptive behavior. Chemical and eruptive trends, or the absence of them, can be established, providing powerful constraints for models of magmatic evolution. A thorough record of volcanic history is invaluable in planning a response to detected unrest in order to anticipate and mitigate eruption impacts.

More than one borehole may be required for a satisfactorily complete record. This is especially true for arc volcanoes, where sector collapse may limit subsequent effusions to a portion of the volcano until conical symmetry is restored. When done properly, much greater temporal evolution over a greater and more continuous interval of time is possible than by the conventional approach of trying to correlate formations among a limited number of dissected ridge exposures.

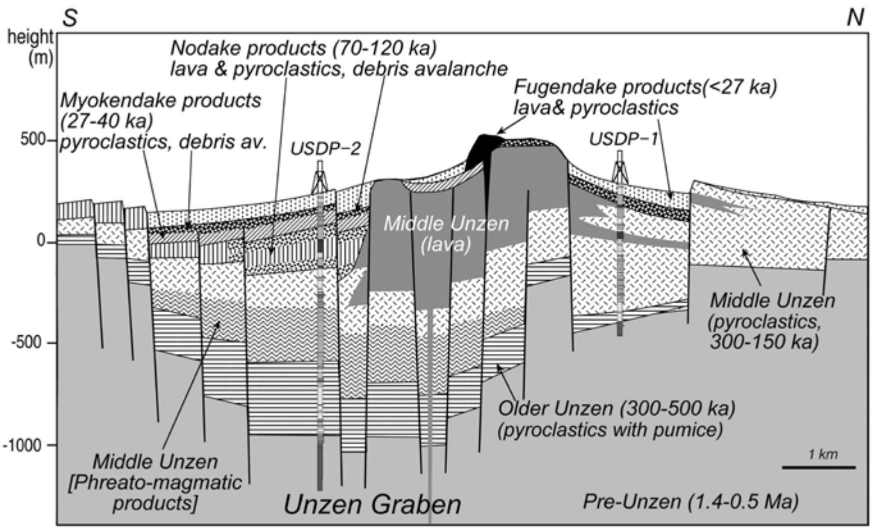

Fig. 3. Phase I drilling at Unzen revealed the growth history of an arc volcano, with coincident development of a graben. Both features appear to reflect establishment of a magma chamber in the mid crust (after Hoshizumi et al. 1999).

An especially important case for these kinds of stratigraphic and structural studies is calderas. A considerable amount of drilling data is available for calderas because they often host geothermal systems and ore deposits. However, these economically motivated boreholes have left some scientific questions unanswered, in particular the extent and nature of post-caldera volcanism and the issue of caldera structure. End-member structural models are a piston-cylinder structure with ring vents fed from ring-dikes, a view first prominently advocated by Smith and Bailey (1968), and a broad funnel-shaped structure formed by collapse surrounding a central vent proposed, for example, by Aramaki (1984) for Aira Caldera in Kyushu, Japan. The former hypothesis is coupled to a large, mostly liquid magma chamber model while the latter to a much smaller and perhaps deeper magma reservoir. It is possible that both views are correct, with the former structure being more common in thick-crust, interior continental environments and the latter in an island-arc or continental margin setting. Nevertheless, neither has been conclusively proven and explored; intermediate systems with both funnel excavation and block subsidence are possible.

Enough geothermal drilling has been conducted in the Valles Caldera of New Mexico, USA, the “type” piston-cylinder system, to show that it is not floored by an unbroken subsided block (Self et al. 1988). Nigorikawa Caldera in southern Hokkaido, Japan, is perhaps the best-defined funnel caldera (Fig. 4, Hanano 2005).

Regardless of how they form, calderas contain within them a large hidden volume of post-caldera volcanic deposits. If we are to understand the assemblage of large magma accumulations in the mid to upper crust, both in terms of their structural and chemical evolution, and even the basic questions such as the true volume of eruptives, then we need to further the exploration of these systems by scientific drilling. In the broadest sense, large silicic calderas may hold the key to how primitive arc crust is transformed into unsubductable continental crust.

5.2 Volcanic Conduits

Conduits are the pathways by which magma reaches Earth’s surface and erupts. That conduits exist is incontrovertible, but how they form, why they are re-used, and their role in influencing eruptive behavior are very much open to question. Conduits are likely initiated as dikes. Magma-filled or gas-filled cracks, not holes, are the first response to magma and associated vapor exceeding the least principle confining stress where magma is stored (e.g., Carrigan et al. 1992; Tait et al. 1992). There are several ways in which direct observation of active conduits inform eruption models and improve eruption forecasting and therefore hazard mitigation.

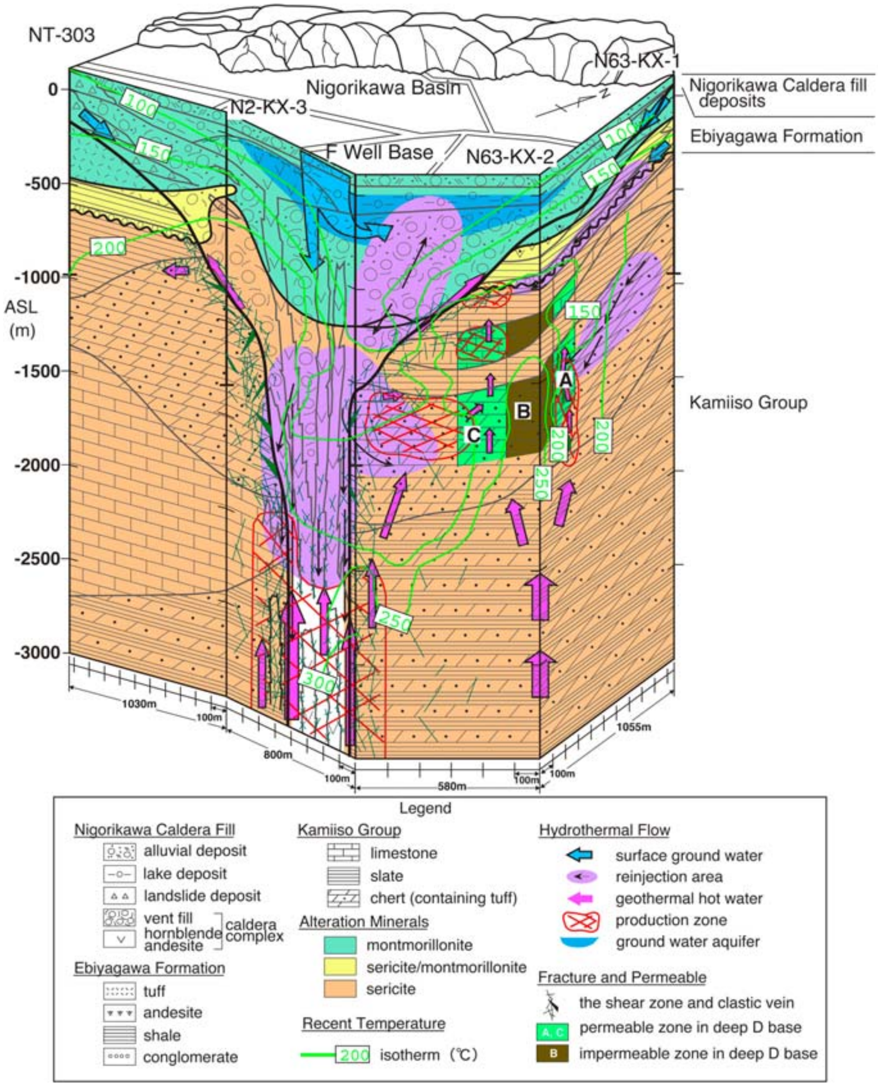

Fig. 4. Nigorikawa Caldera, where both the geothermal system and the structure of a young volcanic vent have been revealed through commercial geothermal drilling (Hanano 2005).

1. **Physical parameters.** Physical dimensions of the subsurface system coupled with surface observation of discharge rate during eruption constrain ascent rate of magma.
2. **Conduit contents as a function of depth**. Magma ascent involves decompression and to a lesser extent cooling. Decompression drives bubble growth and rapid gas loss, and degassing and cooling both force crystallization, which further enhances degassing. Proportions of phases in the multiphase mixture change, as does the composition of the melt. Consequently, bulk physical properties of the system vary through orders of magnitude. We are a long way from fully treating this problem computationally, but direct observation of bubble, crystal, and matrix composition distribution in conduits for monitored eruptions is an important basis for such modeling. It is especially important as an early next step to explore a shallower depth regime than was possible at Unzen, where syneruptive degassing must be more vigorous.
3. **Relationship of conduit properties to eruption**. As mentioned earlier, a conduit has much in common with a borehole and therefore the concepts of borehole stability apply. These may be a key to understanding why eruptions stop. Although effusive eruptions involve a fairly dense fluid occupying the conduit, in explosive eruptions the upper part of the conduit is occupied by a dusty gas (e.g., Mastin and Ghiorso 2000) and therefore grossly underpressured – perhaps leading to collapse. One may well ask whether a sustained explosive eruption requires strong conduit walls capable of resisting collapse. We need to know the mechanical characteristics of conduit walls and of wall structure – as indicated by fracturing and deformation – for explosive eruptions as well effusive eruptions.
4. **Post-eruption heat and mass transport.** Rates of heat loss and chemical alteration, the early post-emplacement processes in conduit magma environment following eruption, can be assessed by drilling conduits shortly after eruption. The Unzen experience shows that cooling rates even at the base of an edifice are very high, so that a decade after eruption is too late to penetrate a high temperature environment. This has implications as to how one eruption will or will not influence the next one and as to the influence of residual heat and hydrothermal alteration in guiding magma to repeat the same path. Hydrothermal alteration surrounding the conduit has also been postulated to be a contributing factor to catastrophic sector collapse (Reid et al. 2001).
5. **Source of shallow inflation and seismicity.** The shallow conduit and wallrock is where geophysical signals precursory to eruption are generated. In particular, both high-frequency earthquakes reflecting brittle

failure as intrusion proceeds and long-period earthquakes, which are thought to arise from fluid – probably magmatic gas and/or heated groundwater – opening and resonating in cracks, come from this zone (e.g., Chouet et al. 1994; Benoit and McNutt 2003). In-situ observations in boreholes directly penetrating the seismogenic volume of restless magmatic -hydrothermal systems would provide insight into the physical properties and processes operating in this still poorly understood environment. For example, time-dependent deformation models are sensitive to rheological properties at depth.

6. **Stress field observations.** Measurement of the stress field in and around conduits using downhole hydrofracture and breakout techniques may lead to a better understanding of why magma intrudes where it does and, possibly, to why some intrusions stop short of the surface (e.g., Kümpel pers. comm.). There is also the interesting issue of how a volcanic system perturbs the regional stress field, although drilling itself may cause stress changes in a seismogenic volume.
7. **Proximal, high signal/noise level monitoring.** The low temperatures that prevail within the Unzen edifice show that instrumentation can be emplaced very close to the conduits of active volcanoes as downhole observatories. Downhole instrument packages, including strainmeters, continuous temperature cables, broadband seismometers, and, perhaps, innovative chemical detectors, may provide both earlier warning of renewed ascent of magma and new insights into how magmatic intrusions are initiated (e.g., Linde et al. 2005). Borehole emplacement greatly increases the signal-to-noise ratio of most kinds of measurements.

The view of ascending magma provided by coring of conduits does have limitations, however. First, this is magma that stopped flowing at the end of the eruption. We do not know how eruptions end; presumably by decline in reservoir pressure attending withdrawal of magma. But if it has to do with changing magmatic properties, then the contents of the conduit may not be representative of magma that erupted. Second, magma undergoes changes following emplacement, including bubble collapse, crystallization, and hydrothermal alteration (e.g., Almberg et al. in press), again yielding material that differs from the erupting system. Still, borehole observation and sampling of conduits is vastly superior to indirect arguments about the subsurface volcanic regime.

Volcanic systems might be envisioned as described by a parameter space with axes of explosivity, magma composition, and repose period (Fig. 5). Unzen represents a system of intermediate composition with minimal explosivity and repose periods of the order of a century (historically, 129 and 199 years). Obvious next steps in this line of scientific drilling investigations are to investigate systems with shorter repose intervals in order to explore a hotter environment, and those with higher explosivity in order to explore the relationship of conduit characteristics on eruptive style, and ultimately the causes of explosive versus non-explosive volcanism. It is vitally important to obtain continuous core across conduits and adjacent wallrock, so that a full understanding of the system and gas pathways can be obtained.

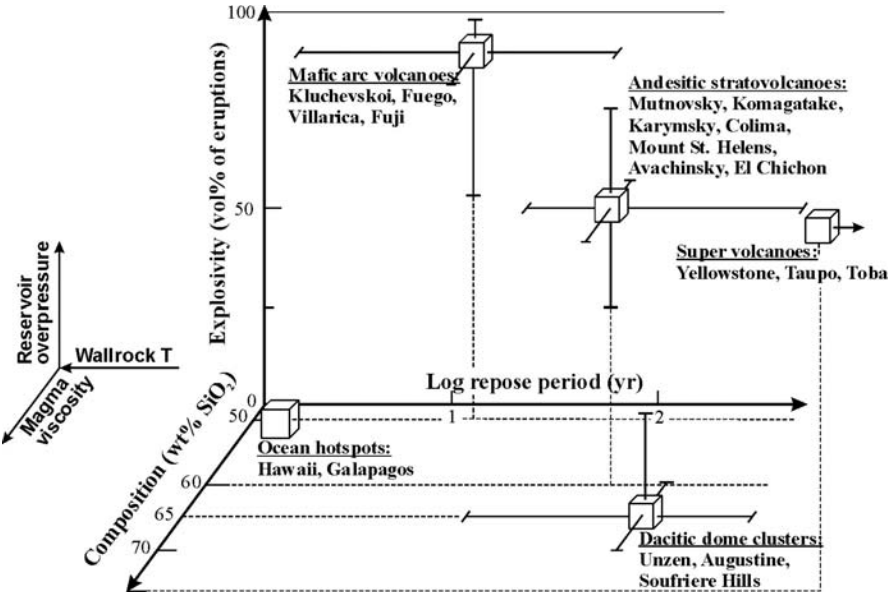

Fig. 5. Viewgraph characterizing active volcanic systems in terms of dominant composition, explosivity, and repose period.

5.3 Magma-hydrothermal Connection

An equally promising area for investigation is the relationship between hydrothermal systems and active conduits or magma bodies. Most high-temperature geothermal fields are spatially associated with active or recently active volcanic systems, and many geothermal boreholes bottom in young intrusions. There is a presumption that magma directly contributes heat and mass to geothermal systems. For example, chloride outflow from hydrothermal systems has been used to estimate crystallization rates of underlying magma at Yellowstone and Long Valley Calderas (Fournier 1999). Fournier suggested that many convective hydrothermal systems are separated from convective magma systems by a relatively thin, plastic, conductive zone characterized by a steep conductive gradient. Excess vapor pressure developed in the magma by second boiling during crystallization, periodically ruptures the plastic zone to introduce magmatic volatiles into the hydrothermal system. The concept of a ductile conductive boundary separating melt-present and acqueous fluid-present regimes is supported by observations made during drilling into Kilauea Iki lava lake (Hardee et al. 1981). At Mutnovsky Volcano in Kamchatka, Russia, the geothermal production zone defines a plane whose southward projection contains the high-temperature conduit of Mutnovsky Volcano (Fig. 6; Kiryukhin pers. comm.). The meteoric water component of the system is isotopically distinctive and resembles that of the crater glacier, also suggesting a direct connection.

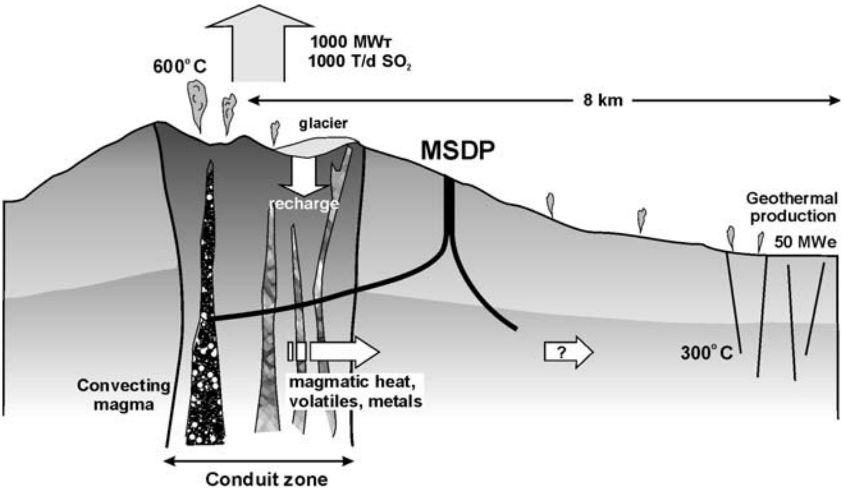

Fig. 6. Geological section through Mutnovsky Volcano in Kamchatka, which provides a case where the magma-hydrothermal connection may be dominantly horizontal and, therefore, readily accessible (MSDP = planned Mutnovsky Scientific Drilling Project).

The magma-hydrothermal connection should be explored for several reasons:

1. **Super- critical systems.** We expect to find higher enthalpy geothermal fluids closer to or deeper into volcanic systems than drilling has previously penetrated. This is supported by high-T metamorphic- and hydrothermal aureoles around plutons in deeply eroded volcanic systems as well as ore deposits and amphibolite facies rock alteration. A simplified model is shown in Fig. 7. The details of the coupling of

magmatic heat sources and hydrothermal systems requires scientific drilling. For reasons of both safety measures and high costs, collaboration with industry is most desirable and will benefit both scientific and economic interest (Friedleifson and Elders 2005).

2. **Hydrothermal "unrest"**. Much of the geophysical "unrest", seismic swarms and inflation, commonly interpreted by volcanologists to be magmatic in origin, may be only indirectly so. A significant proportion of these phenomena may be caused by pressurization and flow of hydrothermal fluids. Additionally, hydrothermal systems are suspected of intercepting or "scrubbing" magmatic SO_2 emissions, complicating the interpretation of volcanic gas emission during periods of unrest (Doukas and Gerlach 1992). Thus, proper use of monitoring data in eruption warnings and hazard mitigation requires understanding hydrothermal as well as magmatic processes.
3. **Managing volcanism**. The time-averaged thermal output of active volcanoes through eruption is of the same order as what is extracted in medium-sized geothermal developments. From a heat budget standpoint, then, it is possible that geothermal development could perturb volcanic systems, perhaps even removing sufficient energy that eruptions would be reduced in frequency and explosivity (Kiryukhin pers. comm.). This is a radical idea, but not an absurd one.

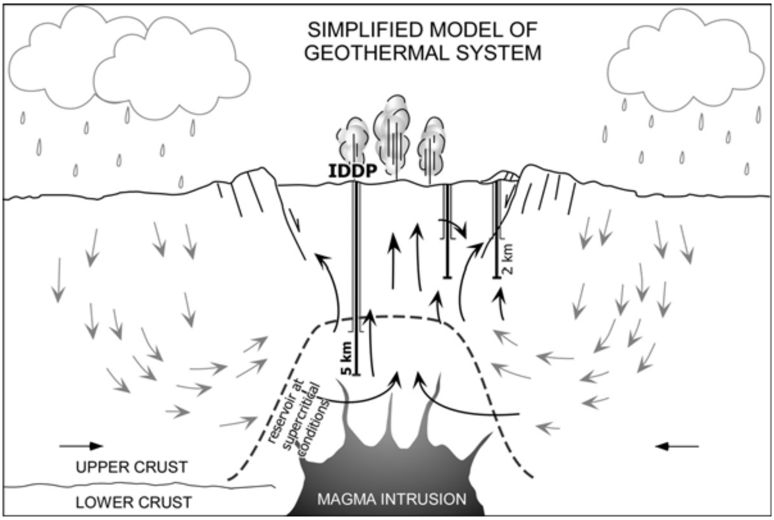

Fig. 7. The Iceland Deep Drilling Program (IDDP) is a partnership between science and industry to explore the supercritical fluid regime, intermediate between the known hydrothermal domain and the hypersolidus domain (Fridleifson and Elders 2005).

5.4 Magma

Inferring the conditions of magma storage in the crust and the processes that magma undergoes during storage is a major goal of volcanology and igneous petrology. In such storage of magma lies the key to understanding the causes of onset and cessation of eruption, the origin of igneous rock suites, the source of heat and mass for hydrothermal systems and ore deposition, and the assembly of granitic plutonic masses and hence the evolution of continental crust.

Volcanic rocks provide only a limited view of the magmatic state. In general, stored magma is a multiphase mixture of crystals and bubbles suspended in silicate melt. During ascent, the melt releases dissolved volatiles, bubbles expand because of this and because of simple decompression. In turn, water loss from melt forces crystal growth. What is erupted is then a variably inflated and crystallized metastable assemblage that has lost most of its volatile components.

There are various ways of inferring initial pre-eruptive magmatic conditions from volcanic rocks. These include geothermometry and geobarometry based upon experimentally calibrated phase equilibria, experimental replication of phase assemblage, and particle beam and infrared beam microanalysis of glass inclusions in crystals. In concert, distribution of seismicity, seismic tomography, and modeling of the pressure source for observed surface displacements may provide corroborating – or in some cases seemingly contradictory - evidence of the extent of the melt-present domain.

There is, as yet, no “ground truth” and the second half of crystallization history of magma is entirely concealed from us. Volcanoes generally erupt material where the pre-eruption melt fraction was 50 vol% or more. Geologic exposures of ancient magma reservoirs reveal only plutonic rocks where crystallization has gone to completion.

This ground truth is technologically within our reach, and it will reveal not only new aspects of the magmatic state but also the coupling between magma and hydrothermal systems, which is expected to be a relatively thin ductile zone of conductive heat transport. The record-setting high-temperature borehole at Kakkonda, Japan (Saito et al. 1998) apparently bottomed in this zone, just short of the solidus. Drilling at Kilauea Iki lava lake in the 1970s and 1980 demonstrated the feasibility of actually coring melt-rich lava, by using large amounts of water and thereby chilling melt to glass in front of the drill bit (Hardee et al. 1981). But lava lakes contain material that fragmented into a spray during eruption, degassed to one atmosphere, and then accumulated as a lake. Drilling through the solidus to unerupted magma will permit us to observe the end-stage of crystallization and the magma chamber boundary, which has been hypothesized to represent a key site in magmatic differentiation (e.g., Hildreth 1981). Quenching of samples by drilling should faithfully preserve magmatic textures and melt volatiles, because quenching occurs ahead of the core bit *in situ* at pressure, rather than after decompression to atmospheric pressure.

Participants in the magmatic processes discussion during the ICDP decadal workshop recommended that reaching the silicate solidus should be a target for ICDP during its second decade. Favorable sites for achieving this goal are well-studied active silicic volcanic systems where abundant seismic, geodetic, and petrologic data provide a consistent picture of shallow magma storage, and/or hydrothermal systems where drilling has penetrated a ~500°C conductive (steep thermal gradient) zone in young intrusive material.

Hypersolidus conduit and magma chamber targets provide different but complementary information. Conduit magma has recently undergone a decompression step with loss of water, to which it gradually responds by bubble collapse and both crystallization and breakdown of hydrous phases. Reservoir magma is near equilibrium, and the marginal zone of a reservoir will reveal the transition from magma to pluton through slow crystallization.

6 Summary

Scientific drilling should be undertaken into active volcanic regimes of the continental crust for the following reasons:

1. To directly observe, through *in situ* measurement and sampling, physical and chemical conditions and processes of mass and heat transport that comprise volcanism and that cannot be observed or sampled in exposed fossil systems. The geometry and structure of magma pathways that have produced thoroughly documented eruptions is of fundamental importance to understanding eruption processes.
2. To obtain a complete record of volcanic output of caldera systems and their structure in order to understand magmatic evolution and the continentalization of arc crust, as well as to properly assess hazards for people living in calderas.
3. To encourage and expand geothermal energy development into higher enthalpy systems.
4. To provide subsurface sites for proximal, high signal/noise monitoring of volcanic unrest.

5. To push explored environments to ever higher temperatures and eventually to the hypersolidus regime, where the keys to central questions of petrology and volcanology lie.

Acknowledgements

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Scientific Drilling of Active Faults: Past and Future

Ze'ev Reches[1] and Hisao Ito[2]

[1]School of Geology and Geophysics, University of Oklahoma
Norman, OK 73019, USA
e-mail: reches@ou.edu (corresponding author)

[2]Center for Deep Earth Exploration, Japan Agency for Marine-Earth Science and Technology, Yokohama, Kanagawa 236-0001, Japan

Abstract

Drilling into active faults has become a major scientific endeavor during the last decade and it appears as a most promising approach to resolve long-standing questions in earthquake and faulting processes. The first boreholes were drilled into the Nojima Fault following the 1995 Kobe earthquake. Since then, drilling into active faults has begun or been planned in a wide range of tectonic settings, such as a strike-slip plate boundary (San Andreas Fault, California), a thrust zone in an active orogenic belt (Chelungpu Fault, Taiwan), a normal fault in an active rift zone (Aigion Fault, Greece), a reactivated Archean fault (Pretorius Fault, South Africa), and a major subduction thrust (Nankai Thrust, Japan).

These projects have already revealed many details on in-situ stresses, fault-zone structure, fault-rock composition, mechanical properties, heat flow, and near-field seismicity. Furthermore, most of these projects will continue to serve as observatories for monitoring fault deformation, fluid pressure and near-field earthquake source processes for a decade or two. Future drilling projects will focus on near-field observations and long-term monitoring of time-dependent processes and in-situ experimentation in active fault zones. Collaboration with industry and government will address practical issues pertaining to petroleum and geothermal energy, radioactive waste disposal, and urban seismic hazards. The outcome of these international efforts in drilling active faults will revolutionize our understanding of the processes controlling faulting and earthquakes and lead to a stronger scientific basis for earthquake hazard mitigation.

1 Introduction

Most earthquake investigations are based on data collected at or near the Earth surface and on the analysis of earthquake rupture zones observed in soils or soft sediments. This situation leads to incomplete sampling of high-frequency seismic data due to wave attenuation in the crust and to lack of representative observations on the earthquake rupture processes in the focal depth. Further, the surface observations provide no option for direct measurements of pore pressure, in-situ stresses, or heat generation that are associated with earthquakes and faulting (Zoback and Emmermann 1994). These inherited conditions of surface observations could limit the needed progress in earthquake science. For example, the National Research Council (2003) identified specific long-term research goals in earthquake science:

1. Fault recognition: location, slip rate, and earthquake history
2. Earthquake forecasting as function of location, time, and magnitude
3. Fault-system dynamics: The kinematics and dynamics of interacting
4. Fault-zone characterization: three-dimensional structure and material properties of fault-zones
5. Earthquake source: nucleation, propagation, and arrest in realistic fault systems
6. Ground-motion and nonlinear response of surface layers
7. Seismic hazard analysis
8. Develop reliable information systems for rapid alert and
9. Partnerships between earthquake scientists and other communities.

Seismic observations at the Earth surface are restricted in addressing goals 2 to 7 above due to the lack of direct and near-field data. On the other hand, studying earthquakes by drilling active faults or by using the infrastructure of deep mines could remove some of these restrictions.

This central advantage of drilling was the main drive for the initiative of Zoback and Emmermann (1994 p. 47-69), in which they projected that drilling active faults will provide better answers to the fundamental questions of earthquake science. These questions are being investigated in scientific drilling projects, such as the Nojima fault drillings, San Andreas Fault Observatory at Depth (SAFOD), Drilling Active Faults in South African Mines (DAFSAM), Corinth Rift Laboratory (CRL), and Taiwan Chelungpu-fault Drilling Project (TCDP). This paper outlines questions and answers addressed in these projects.

2 Past and Present Scientific Drilling into Active Faults

2.1 A Large Strike-slip Fault in an Island Arc: Nojima Fault

Immediately after the 1995 Kobe earthquake (M=6.9), the Geological Survey of Japan (GSJ), the National Research Institute of Earthquake Science and Disaster Prevention (NIED), and an University group drilled boreholes along segments the Nojima fault that exhibited surface rupture during the earthquake. The boreholes depths ranged from 747 m to 1800 m. The three groups made extensive logging, detailed core analysis, and stress measurements, as well as temperature logging (NIED, University Group), repeated hydrological tests (GSJ), and repeated injection tests (University Group). The preliminary results were published in the special volume of the Island Arc (Oshiman et al. 2001). Integrated borehole systems (3-component strain meter, 3-component seismometer, and water-level sensors) were installed at the center part of the Nojima fault (by GSJ), and its southern end (by the University group).

The GSJ and NIED boreholes at Hirabayashi, where the maximum slip of 2 m was observed, penetrated the core of the Nojima fault, which allowed to study seismic and aseismic slip deformation features, and to measure the physical properties of the fault zone (Ito et al. 1996; Tanaka et al. 2001; Ohtani et al. 2001; Fujimoto et al. 2001; Boullier et al. 2001). The major findings of the fault structure indicate that the Nojima fault zone is characterized by a narrow fault core with three types of fault gouge, the hanging wall of the fault displays many minor shear zones; also observed an increase toward the fault core of brown feldspar and decrease of mafic minerals (Fig. 1). The footwall of the fault is significantly less deformed and less altered with respect to the hanging wall.

Tadokoro and Ando (2002) analyzed the shear wave polarization associated with aftershocks of the 1995 Kobe earthquake. They showed that while the fast shear direction was parallel to the Nojima fault strike until 12 months after the Kobe earthquake, it changed into E-W direction (parallel to regional stress orientation) in the period of 33-45 months after the earthquake. They interpreted this observation as indicating fracture healing: immediately after the large earthquake, fractures of shear fault origin are created subparallel to the active fault, then their density decrease with time as they heal.

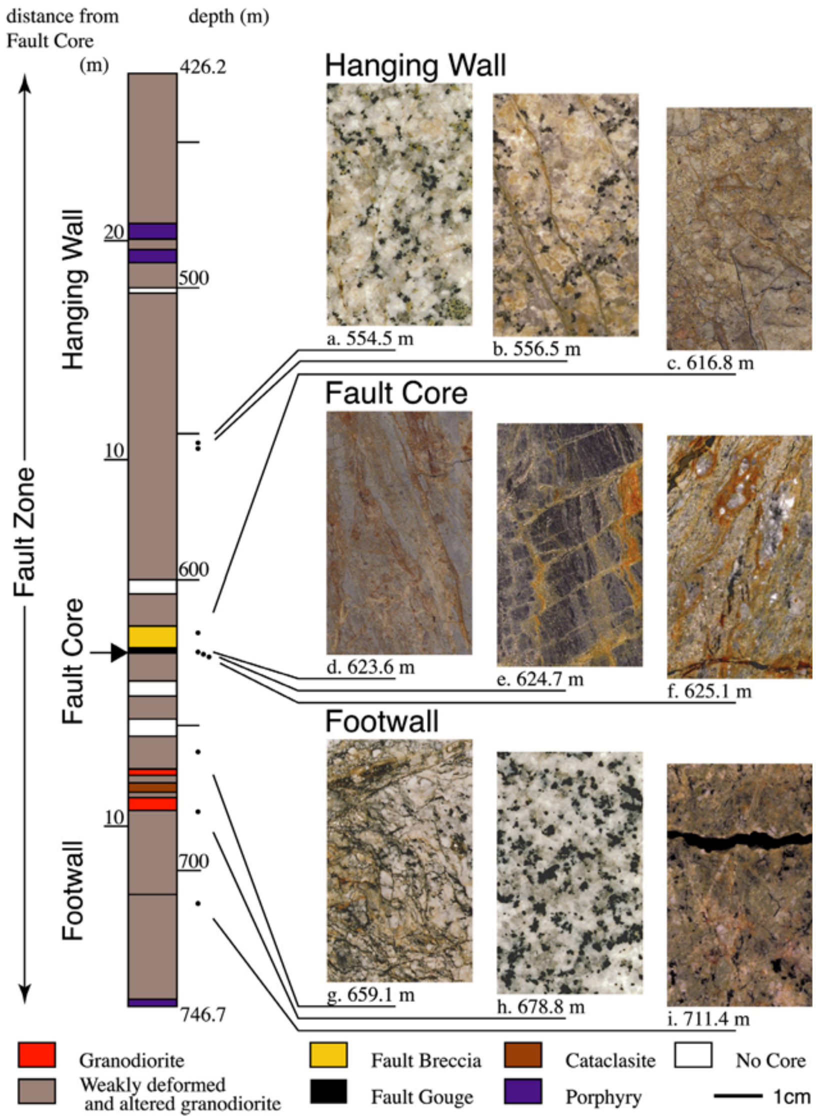

Fig. 1. Fault rocks in the fault-zone of the Nojima Fault, Japan, as observed in the borehole of the Geological Survey of Japan; see text (after Ando 2001).

2.2 A Major Transform Plate Boundary: San Andreas Fault

The San Andreas Fault Observatory at Depth (SAFOD) is located in Parkfield, California, 1.8 km southwest of the surface trace of the San Andreas

Fault (Fig. 2) (http://safod.icdp-online.org). Because of its propensity for regular earthquake activity, a wide range of geophysical and geological investigations were carried out the Parkfield region since 1985 as part of the earthquake prediction experiment of the US Geological Survey (Roeloffs 2000), and in preparation for SAFOD drilling (Hickman et al. 2004). The SAFOD Pilot Hole was drilled in 2002 to lay the scientific and technical groundwork for the Main Hole. The Pilot Hole has been used for collecting seismic data and monitoring deformation and fluid pressure (Hickman et al. 2004). The SAFOD Main Hole was drilled in two phases (2004 and 2005), as part of the EarthScope program funded by the National Science Foundation.

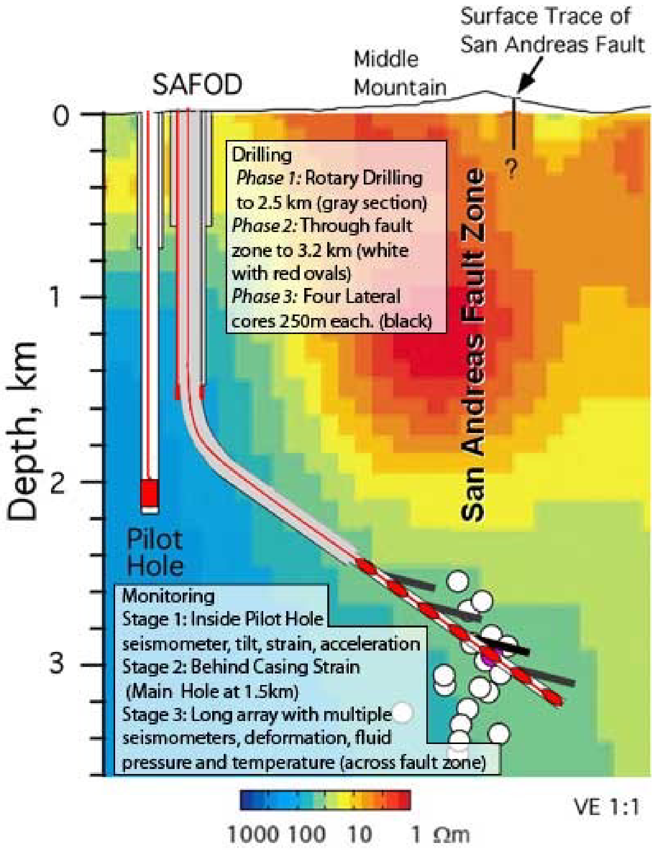

Fig. 2. Long-term and near-field monitoring in SAFOD Observatory. Stage 1 (Pilot hole): seismometers and tiltmeters; Stage 2 (Main Hole): Laser strainmeter, seismometers and accelerometers; Stage 3 (Off-shoot holes and Main hole): seismometers, accelerometers, tiltmeters, pore pressure and temperature gages (after http://safod.icdp-online.org).

The Main Hole was drilled vertically to 1.5 km and then steered northeast to a vertical depth of 3.1 km, taking it through the San Andreas Fault. In the third phase (2007), four multilateral core holes will be drilled off the Main Hole, each extending approximately 250 m into regions with repeating microearthquakes in the San Andreas Fault Zone (Fig. 2). The Main Hole is being outfitted as a long-term fault observatory that will collect data for at least the next 20 years. Observatory-mode monitoring will include near-field, wide-dynamic-range seismological observations of earthquake nucleation and rupture as well as continuous monitoring of pore pressure, temperature and strain during the earthquake cycle. The major data products from the SAFOD project include physical samples (e.g., core, cuttings, and fluids) from the fault zone and surrounding crust, geophysical measurements (e.g., well logs, hydraulic fracture tests), and monitoring data (e.g., seismic, temperature).

The drilling and logging in SAFOD Main Hole revealed a broad, ~250 m, fault-zone of the San Andreas Fault, characterized by intensely damages rocks (low wave velocities). A few narrow zones of localized active slip were recognized inside the broad damage zone, and the slip magnitude and slip nature (creep or seismic), along these narrow zones were determined by repeated surveys of the borehole casing and recording of microearthquakes (Zoback et al. 2006). It was found that the fault-zone separates two hydrologic regimes with higher pore pressure and distinct geochemistry in the NE block of the San Andreas. However, no evidence of elevated pore pressure is found within the fault-zone of the San Andreas. The measurements of in-situ stresses (Hickman and Zoback 2004) and heat flow in the SAFOD boreholes are in agreement with the long-standing analyses, which indicated that the San Andreas Fault is weak relatively to the stronger crust on both its sides.

2.3 A Major Thrust in an Active Orogenic Belt: Chelungpu Fault

The 1999 M 7.7 Chi-Chi earthquake in Taiwan produced large zones of surface rupture, with a maximum displacement of 8 m on the Chelungpu Fault. The north portion of the fault is characterized by low damage, large slip and slip velocity, and relatively low acceleration, suggesting that this portion of the fault slipped “smoothly.” The Taiwan Chelungpu-fault Drilling Project (TCDP) framework defined the main scientific objectives and rationale for the drilling as follows (Mori et al. 2002; Ma et al. 2006) (http://www.icdp-online.org): (1) The dense seismic instrumentation in Taiwan allows accurate modeling of the slip and slip velocity distribution of the Chi-Chi earthquake, and the identification of an asperity with displacements of 10-15 m at shallow depths. This is an ideal site to drill to an asperity for testing various mechanisms of nucleation and rupture of large earthquakes. (2) The drilling could provide answers to fundamental questions on the relations between the Chelungpu thrust and regional tectonics. For example, does the main fault zone remain sub-horizontal, causing "thin skin" deformation across central Taiwan, or does the fault zone steepen into the mantle, producing "thick skin" deformations?

TCDP drilling was started in 2004 and two boreholes were completed in 2005, including successful continuous coring, logging and borehole monitoring. In Hole-A, ten fault-zones were identified in the Pliocene Chinshui Shale and Miocene Kueichulin Formation. The shallowest one at depth 1111 m is considered as the fault zone that ruptured during the Chi-Chi earthquake (Fig. 3). This fault is associated with bedding-parallel thrusting with a gentle dip of about 20° and is characterized by over 1 m of gouge (fault core) and gradational breccia to protolith zonation (damage zone) in both the upper and lower blocks (Fig. 3). The observed inclination of the active fault-zone implies that the Chelungpu Fault may cut up-section from depth to the shallow horizon of the Chinshui shale.

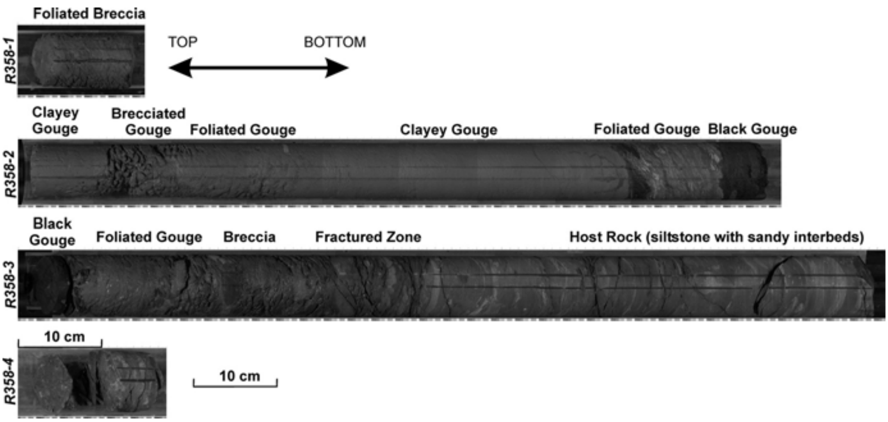

Fig. 3. Core of the fault-zone at depth 1111 m in Hole–A of TCDP. This fault-zone is the most likely fault that slipped during the Chi-Chi earthquake. Note the meso-structures and thick shale zones (http://chelungpu.icdp-online.org).

2.4 A Normal Fault in an Active Rift Zone: Aigion Fault

The Corinth Rift Laboratory (CRL) project drilled into the Aigion fault, Gulf of Corinth, Greece, which is one of the most seismic regions in Europe. This site offers excellent conditions for in-situ investigation of earthquake sources, for developing seismic hazard reduction procedures, for better understanding of the rifting processes, and for monitoring fluid-fault interactions (Cornet et al. 2004). This rift zone is also a currently active analogue of the North Sea region that was active some 20 million years ago, and thus, CRL can provide better understanding of the largest hydrocarbon resources in Western Europe.

The AIG10 borehole was drilled in 2002 to 1000 m depth and it intersected the Aigion Fault at 760 m (Fig. 4). The laboratory operations focus on analysis of faulting processes from both quasi-static and dynamic points of view, through direct in-situ observations and experimentation. A key goal of the Laboratory is to understand the relationships between outcrops of steeply dipping fault-zones and the deeper seismogenic sources. Special attention is directed to the interactions between circulating fluids and fault mechanics, including hydro-thermo-mechanical coupling and the role of healing and alteration. Similarly to the San Andreas Fault (see above), the Aigion fault-zone forms a hydraulic barrier that sustains a 0.5 MPa differential pressure; the highly karstic limestone in the footwall is continuous down to 1000 m, with 0.9 MPa overpressure and isothermal temperatures. Geochemical data indicate a shallow continental origin of this water, and the absence of deep fluid input from the mantle. The present monitoring of downhole pressure yields data on tidal variations, as well as pressure variations induced by teleseisms. The preliminary ^{14}C dating results suggest that the fault is about 50 ka old with mean slip rate of about 3.5 mm/y.

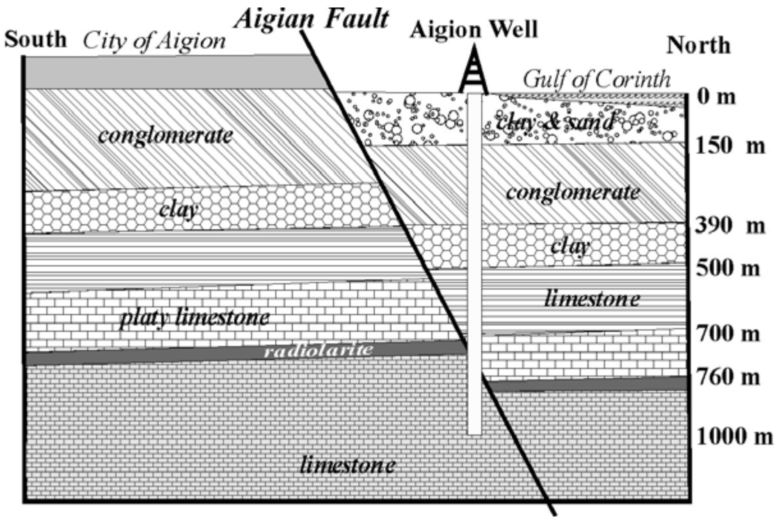

Fig. 4. Schematic structural cross section through the Aigion Fault, Gulf of Corinth, Greece (after Cornet et al. 2004).

The CRL team proposes to drill a 4.5 km deep borehole that would allow monitoring transients in pore pressure within the seismogenic zone and providing clues to the origin of deep fluids. It would also provide rock samples for determination of the rheological properties of fault rocks to constrain proposed models for the temporal and spatial variations in the slip surfaces.

2.5 Reactivated Faults in Deep Gold Mines

The deep gold mines of South Africa offer unique environments to study earthquakes by providing access to the focal area (McGarr et al. 1979). The mining operations generate thousands of earthquakes per day, and some of these events approach M 5. Two research groups used this setting.

In 1992, a group in Japan initiated a research program on semi-controlled earthquake generation experiment in the deep gold mines of South Africa (Ogasawara et al. 2002). The main initial objectives were to monitor temporal variations in strain and seismicity in close proximity to hypocenters activated by mining operations. The operations included installations of the Isii strain meters and broadband seismic systems in several mines, and continuous monitoring of normal and shear strains in the proximity of faults that generate earthquakes at depths down to 3 km (Ogasawara et al. 2002). Recently, this group started an experiment in Mponeng mine at 2,900 m depth to measure the heat production during earthquakes (Nakatani, et al. 2004). They drilled seven short holes across a single weak fault surface within the Pretorius Fault Zone, and installed a network of thermistors. Continuous monitoring of temperature in proximity to this fault will allow to determine the heat production (and hence the frictional resistance) during the anticipated earthquake. These studies revealed that the source parameters for mine earthquakes in the range of M=0.8～1.4 are essentially the same as for larger natural earthquakes (Yamada et al. 2005). The proximity to the fault allows high strain resolution, yet Ogasawara et al. (2005) reported that no acceleration in the deformation was detected prior to the monitored events.

The Natural Earthquake Laboratory in South African Mines (NELSAM) is another project that utilizes the advantages deep mines for earthquake research (Reches et al. 2006) (earthquakes.ou.edu). The central part of this project is dense instrumentation and detailed characterization of a large fault-zone in TauTona mine, which is the deepest mine on Earth located within the Western Deep Levels of the Witwatersrand basin, South Africa. The laboratory is built around the Pretorius fault that it is at least 10 km long with 30-200 m of displacement, and which has been inactive for the last 2.5 Ga. The mining plan for the next few years is likely to induce earthquakes of significant magnitude (M > 2) along this fault (Fig. 5). The operation at the site started in 2005 with site characterization, including mapping of 3D structure and composition of the Pretorius fault-zones with emphasis on segments that were reactivated during recent earthquakes, in-situ stress analysis, and drilling of five boreholes, 20-60 m in length, across the 30 m wide Pretorius fault-zone. Once completed, the earthquake laboratory will include a dense array (250 m footprint) of accelerometers (3D broadband, up to 15 earth acceleration), seismometers, strain-meters, temperature sensors, creep-meters, electromagnetic radiation system, and acoustic emissions. Fault-zone fluid chemistry will be monitored with on-site mass-spectrometer.

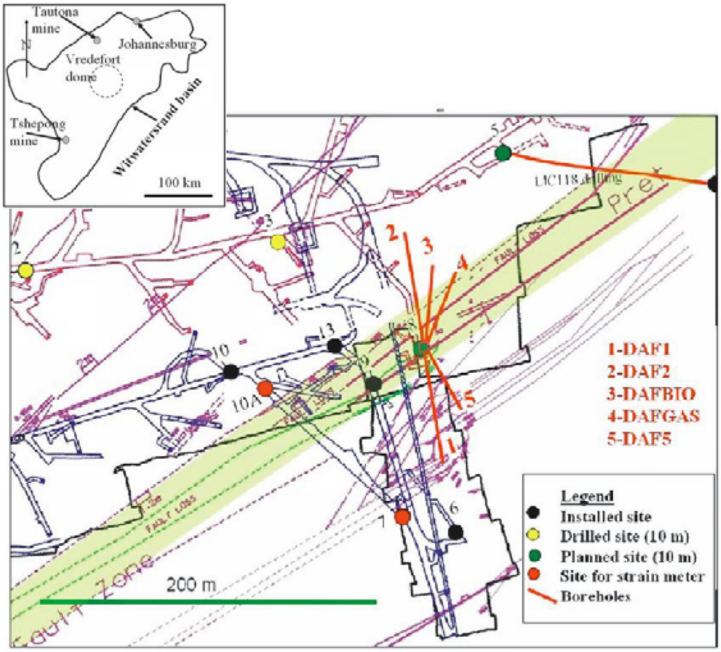

Fig. 5. Site design of the DAFSAM-NELSAM project in Tautona gold mine, South Africa. The figure is a map at levels 118-120 (depth range of 3597 m to 3657 m). Red lines: five boreholes with creepmeters and thermister arrays; blue lines: tunnels; brown lines: faults; red (small) solid circles: sites of 3D broad band accelerometers and seismometers (20 systems) and SP; colored circles: hypocenters of earthquakes 2.0 < M < 3.4 since February 2000.

The preliminary results show that an M 2.2 earthquake of December 12 2004, which occurred in the center of the planned earthquake laboratory, reactivated 2-4 segments of the Pretorius fault (Heesakkers et al. 2005). The 3D mapping of the rupture zone of this earthquake revealed quasi-planar, crosscutting reactivated segments with inclinations ranging 21°to 90°. The rupturing formed fresh fine-grained white rock powder almost exclusively along the contacts of the ancient, sintered cataclasite and the quartzitic host rock.

3 Challenges for Future Drilling Projects

3.1 Overview

The concepts and objectives for future drilling are guided by contributions from three main sources. The first is the cumulative experience of scientific drilling in general, and drilling into active faults in particular. These projects reveal the capabilities and limitations of direct probing of faulting and earthquakes processes at depth, and should guide selection of realistic options for the future. Second, current geodynamic investigations, such as EarthScope (earthscope.org), which generate new ideas and avenues for linking drilling projects to complementary field research at a larger scale. Third, it is anticipated that collaboration with industry and government agencies will increase in the near future to the benefit of all sides. These future collaborations could follow the examples of Mallik Gas Hydrate wells, or the involvement of industry technology experts in downhole measurements and monitoring in SAFOD.

The approaches and emphases for future drilling will probably differ from the operations of the first decade of International Continental Scientific Drilling. It is anticipated that future expansion will focus on (1) Near-field monitoring of time-dependent processes; (2) In-situ experimentation; (3) Collaboration between scientific and economic projects; and (4) Technological developments.

3.2 Near-field Monitoring

3.2.1 Near-field Observations

One of the main obstacles in earthquake investigations is the lack of direct, near-field observations, and the answers to some key questions can be resolved only by direct observations close to the earthquake source (Ellsworth et al. 2001). One such question is whether the final size of an earthquake can be determined during the nucleation stage (Ellsworth and

Beroza 1995). As the nucleation region of an earthquake is small, and as its characterization requires high frequency data, this question can be investigated only in the near field, and avoiding inelastic wave attenuation between the hypocenter and surface stations. Source parameter analysis is also affected by this attenuation, and significant progress has already been made with near-source recordings in boreholes (Abercrombie 1995; Prejean and Ellsworth 2001; Stork and Ito 2004). Drilling into active faults significantly reduces this limitation by investigating seismogenic processes at focal depths.

3.2.2 Time-dependent Processes

Many scientific drillings are devoted to the characterization of composition, structure, and properties of their target at crustal depth. This is a "static" characterization because the observations do not vary during the lifetime of the project. For example, no temporal changes in properties or conditions are expected to occur during the drilling and maintenance of impact craters targets or Quaternary lake deposits. Drilling active faults is a different story and the timing is critical. The relative time with regard to nearby episodic earthquakes is crucial for interpreting the results of downhole measurements, sampling and monitoring; for this reason, several of the current projects are defined as natural laboratories or observatories. One can distinguish between two types of time observations: high-speed phenomena associated with the seismic event, and slow phenomena related to the build up to those events as outlined below.

High-speed dynamic activity. The main task for the next phase of SAFOD (2007) is to drill four sub-horizontal offshoots from the main borehole (Fig. 1). One of these offshoots will be targeted to hit a site of repeated earthquakes of M~ 2.0, which ruptured the same "patch" on the fault at recurrence intervals of about 2-3 years (Nadeau et al. 2004). Tomographic analysis of the recorded seismic events indicates that the absolute location errors of the potential earthquakes are about 50 m horizontally and vertically, and the average of the location calculations places the target event epicenter within about 100 m of the surface trace of the San Andreas Fault (Thurber et al. 2004). Hitting this 'patch" presents the opportunity to monitor an earthquake on a major fault from inside the rupture zone (or very close to it). The instruments in this offshoot borehole will monitor high-frequency data related to earthquake nucleation and rupture processes (e.g., seismicity, deformation, fluid pressure, and temperature) through multiple earthquake cycles.

Similarly, the TCDP project of in Taiwan focuses on measuring a wide range of parameters (imaging, pore pressure, permeability, stratigraphy, static stress levels, and residual temperatures) from the Chi-Chi earthquake, as well as continuous seismic, thermal, and pore pressure monitoring within the active Chelungpu Fault Zone (http://www.icdp-online.de/contenido/icdp/front_content.php?idcat=662; Ma et al. 2003).

Slow phenomena of the earthquake cycle. Boreholes across and near active faults allow to monitor, in the near field, the slow processes that prepare the fault zone for an earthquake, and the processes that are associated with the post-earthquake relaxation. These slow phenomena include temporal variations of strain/stress, creep, heat flow, and pore pressure, as well as electromagnetic phenomena.

After the 1995 Kobe earthquake, several boreholes were drilled along the Nojima fault that ruptured during the earthquake. Rapid changes were observed in aftershock focal mechanism (Yamada et al. 2001) and S wave splitting (Tadokoro and Ando 2002). Yamashita et al. (2004) estimated the stress field before and after the 1995 Kobe earthquake, and found that the fault-zone was completely coupled before the earthquake.

It is anticipated that during its 20-year lifetime, the SAFOD project will monitor multiple cycles of M ~ 2 earthquakes at distances from less than a few tens of meters to about 1.5 km (Hickman et al. 2004). The primary fault-zone monitoring plan consists of a removable array with multiple levels of 3-components seismometers and accelerometers, tiltmeters and thermistors; formation pore pressure will be monitored in one of the multilateral core holes where it crosses the fault patch that ruptures in these recurring earthquakes. This cross-fault monitoring array is being augmented by repeat gyroscopic directional surveys and casing deformation logs in the Main Hole (to identify zones of casing shear accompanying creep and/or earthquakes), a high-resolution (1 nanostrain) fiber optic strainmeter cemented behind casing in the Main Hole at 1.5 km, and a removable seismometer, accelerometer and tiltmeter sonde deployed in the Pilot Hole at 1 km.

3.3 Interactive Experimentation

3.3.1 Fluid Injection

Scientific drilling in tectonically active regions, and particularly into active faults, offers unique experimental opportunities. Kümpel et al. (2006) reported a long-term experiment of production and injection in the pilot hole of the KTB project. The first part of the experiment included a one-year

(2002-03) production of 22,300 m^3 of saline crustal fluids pumped from a fault-zone at 4.0 km depth. The water level and seismicity were monitored continuously in both the KTB main and pilot hole. After one year of recovery, a second, one-year fluid injection test started in June 2004. No significant seismic activity was observed in the first four months of injection, induced seismicity started to be recorded in October 2004 and continued to increase slowly with time. The subsurface data were supported by surface measurements of electromagnetic field, nano-radian tilt monitoring, and high-resolution seismic surveys in an attempt to image the hydraulic expansion of the fault-zone. Similar hydraulic testing is planned for the 7.2 km deep fault system in the main KTB hole (Kümpel et al. 2006).

Induced seismicity by fluid injection has been studied in uncontrolled cases (Raleigh et al. 1976), and in an attempt to reduce earthquake hazards in deep mines in South Africa (Lightfoot and Goldbach 1995). Several water injection experiments into the deep borehole (1800 m) across the Nojima fault-zone were carried out in 1997 and 2000. During the 1997 experiment, the seismicity increased in the region 1-2 kilometers away to the injection borehole about 4-5 days after the beginning of the injection (Tadokoro et al. 2000). These earthquakes of magnitudes -2 to +1 were attributed to the injection. The permeability estimated from the time lag is 10^{-14}–$10^{-15} m^2$, and the friction coefficient estimated for the induced earthquakes was < 0.3. The repeated injection tests revealed permeability change with time. It was also shown that the fault-zone has high hydraulic diffusivity and acts as a conductive body, in agreement with borehole logging results (Kiguchi et al. 2001). It appears that the fault-zone could slip with small increase of pore fluid pressure or shear stress.

It is likely that similar, and more advanced, experiments of fluid injection into or near active fault-zones will be conducted in the future. This experimentation and the analysis of the induced seismicity are likely to become an integral part of the collaborative studies with the energy industry and government agencies.

3.3.2 Rapid Response Drilling

The timing of drilling may be critical for capturing the fundamental features of an earthquake. Several drilling projects were conducted after a major earthquake, e.g., the TCDP and the Nojima Fault drillings; it would have been an outstanding experiment if these boreholes had been drilled before the earthquake. Although the primary purpose of SAFOD monitoring was to capture transient processes associated with recurring small-magnitude earthquakes on the San Andreas Fault, it was also hoped to capture the long-delayed Parkfield M 6 earthquake that repeatedly ruptures the

San Andreas Fault south of SAFOD. This M 6 event occurred on September 28, 2004, after the completion of SAFOD Phase 2 drilling, but too early for the full deployment of the SAFOD observatory.

Another example of the significance of the timing of drilling is related to the frictional heat generated by earthquakes, which is a central puzzling problem of earthquake mechanics (Lachenbruch and Sass 1980). While the largest component in the earthquake energy budget is frictional heat, there are no direct measurements of this parameter for large earthquakes. Such measurements would contribute substantially to understanding rupture dynamic, weakening mechanisms, thermal pressurization, and resolution of the heat flow paradox. The difficulty of conducting such measurements was demonstrated for the M7.9 Denali earthquake of 2002 (D. Lockner, written communication, 2005). With surface rupture length > 300 km and slip magnitude of > 5 m, this earthquake could be an ideal site for drilling at moderate cost (~$200,000 U.S. for a 750-m-deep borehole). However, the time needed to raise the necessary funds was probably too long to detect a sufficiently strong thermal signal. To facilitate measuring frictional heating generated by a similar-sized earthquake, which will certainly occur somewhere in the world during the next few years, drilling plans and funds should be ready long before the event. We believe that a concerted international effort to plan and obtain funding for such an event in advance would be a very fruitful endeavor. Recently, Kano et al. (2006) succeeded in observing a small amplitude temperature anomaly that generated at the time of 1999 Chi-Chi earthquake.

3.4 Collaboration with Economic and Societal Projects

3.4.1 Seismic Hazard Challenges

The evaluation of maximum expected ground motion is a critical component for the design and approval of major facilities; the nuclear waste repository at Yucca Mountain, Nevada, is an outstanding example of this need. The regulations for the Yucca Mountain site require design for very rare earthquakes (probability < 10^{-4}) during very long periods (> 10^4 years). Extensive geological, geophysical and engineering studies were conducted at this site to determine likely earthquake ground motion for such periods (http://www.ocrwm.doe.gov/ymp/). A few modeling procedures yielded high values of peak ground acceleration and velocity (e.g., V_{peak} ~ 13 m/s) with large uncertainties for the largest (and rarest) events (Hanks et al. 2004). These uncertainties stem, in part, from limited information on the effects of variations in seismic velocities, densities, and nonlinear dynamic properties on seismic radiation, wave propagation effects and site response. Andrews (2005) calculated the effect of nonlinear properties of the Solitario Canyon fault-zone for estimated values of the rheological properties and structure at depth and the rock mass below the Yucca Mountain repository. He showed that the internal structure of the fault-zone and its properties have a profound impact on the expected ground motion about 1 km away. These properties, which are currently only estimated, could be determined by dedicated drilling to suitable targets.

The need for safe design of public facilities in major cities that are close to active faults requires detailed knowledge of the anticipated ground motion, and the near-field radiation from the large faults. The simulations of the ground motion depend on knowledge of the real 3D structure of the fault-zones and their associated damage zones at seismogenic depth (Andrews 2005). This need for better, more relevant information on active fault-zones in metropolitan regions will drive future collaboration between scientists and government agencies. Such projects could also be linked to research in development of more reliable early warning systems in urban areas (Wu and Kanamori 2005). These systems are based on fast collection and processing of seismic data starting at the early stages of a significant seismic event, and allow for early deployment of emergency response personnel and quick action to preserve critical gas and electricity supply distribution system. Drilling into active faults will provide the data on structure and physical properties that is needed to for realistic models of strong ground motion. Further, installation of seismic systems at depth could significantly augment surface-based early warning systems in urban areas.

3.4.2 Energy-related Research

Many existing geothermal energy projects take advantage of heat and fluid transport along active faults that require understanding of the relationships between faulting, natural and induced fractures, in-situ stress, and fluid/heat transport (Pine and Batchelor 1984; Willis-Richards et al. 1996; Hickman et al. 1999; Tezuka and Niitsuma 2000). There have been several scientific-industry-government collaborations; for examples, the Dixie Valley (Nevada) and Coso (California) projects were funded by U.S. government agencies with significant cost sharing from the industry partner who runs the field. Similar projects with intense component of induced seismicity are underway or completed elsewhere in Japan, Europe, and Australia.

The basic research approach in geothermal projects is to compare fracture orientations (from core and borehole images) and measured in-situ stresses, with focal mechanisms associated with injection induced events and flow paths. Hickman et al. (1999) analyzed the fracture systems in producing and the non-producing wells in the Stillwater fault zone of Dixie Valley geothermal project. They found that producing fractures are optimally oriented for shear failure with respect to the active stress field, and are subparallel to the Stillwater fault. Tezuka and Niitsuma (2000) showed, for Hijiori hot dry rock project, Japan, that the growth direction of the geothermal reservoir is strongly controlled by the distribution of favorably oriented pre-existing fractures and their interaction of the stress field. One project in progress is the geothermal project in Basel, Switzerland, in the Rhine graben, and about 150 km south of the Soultz geothermal field (Fig. 6). The injection of cold water to 5 km depth and the production of hot water and steam are likely to trigger earthquakes close to a large city; this hazard led to science/industry collaboration in installation and continuous monitoring of natural and production-induced seismicity (Deichmann et al. 2005).

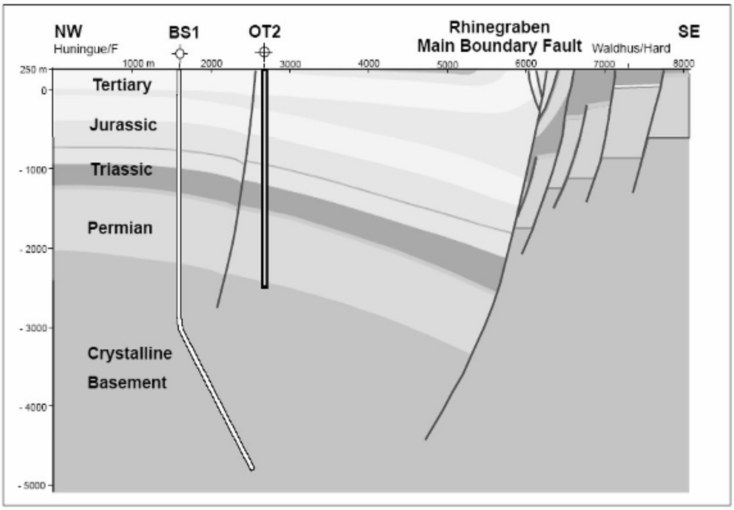

Fig. 6. Monitoring wells OT2 and injection well BS1 in The Basel Deep Heat Mining Project, Switzerland (after Deichmann et al. 2005).

It is not surprising that the oil and gas industry faces similar questions on the relationships between faults, natural and induced fractures, in-situ stress, and fluid flow (Finkbeiner et al. 2001). However, it seems inappropriate to use the limited budget of scientific drilling for research in the multibillion hydrocarbon industry. Potential links between active faults research and the hydrocarbon industry are issues related to fault-sealing (what controls the seal and non-seal modes of active faults) (Jones and Hillis 2003), induced mircoseismicity and fault reactivation (Segall et al. 1994; Wiprut and Zoback 2000). Many of these same questions are relevant to commercial and potential geothermal systems, where faults can act as either barriers or conduits to the flow of high-temperature fluids.

3.5 Needed Developments

3.5.1 Technology Development

Although instrumental observations have been conducted in deep boreholes and deep mines [United States (SAFOD), Japan (Nojima fault, western Nagano region), Europe and South Africa], new methods are needed for long-term monitoring of deformation, seismicity, and pore pressure in the near-field of earthquakes. For example, this requires the ability to measure strain changes in the range of 10^{-12} to 10^{-2}, as accumulated and released during the earthquake cycle, and the need for seismic sensors that cover frequencies from 0.01 Hz to several kilohertz with wide dynamic ranges.

Equipment and techniques for deploying removable instrumentation and multiple sensors systems that can operate at high temperature must be developed. Developments in drilling, coring and core handling technologies are also necessary, especially for recovering fragile fault zone samples. New developments in Logging While Drilling and logging while coring technologies are also needed to adequately characterize and sample the near-fault environment. Real-time mud gas logging is useful in characterizing major influx zones during drilling, supplemented by improved methods for down-hole fluid sampling using wireline and drill-pipe-deployed techniques.

3.5.2 The Link between ICDP and IODP

More than 90% of the global seismic energy is released in subduction zone earthquakes, and thus drilling seismogenic subduction zones is a central theme in the Integrated Ocean Drilling Program (IODP; www.iodp.org). The Nankai Trough subduction zone, Japan (Fig. 7), is a promising site for fault-zone drilling, with the main objectives of characterizing in-situ properties of the megathrust, monitoring long-term fault conditions, investigating the shallow aseismic to seismic transition, and studying earthquake processes and tsunami generation mechanisms. These targets are in accord with the objectives of ICDP for scientific drilling into fault zones on land. Thus, a strong collaboration should form between ICDP and IODP to study active fault zones at both convergent and transform plate boundaries.

This collaboration would also require construction of an integrated land-ocean monitoring network.

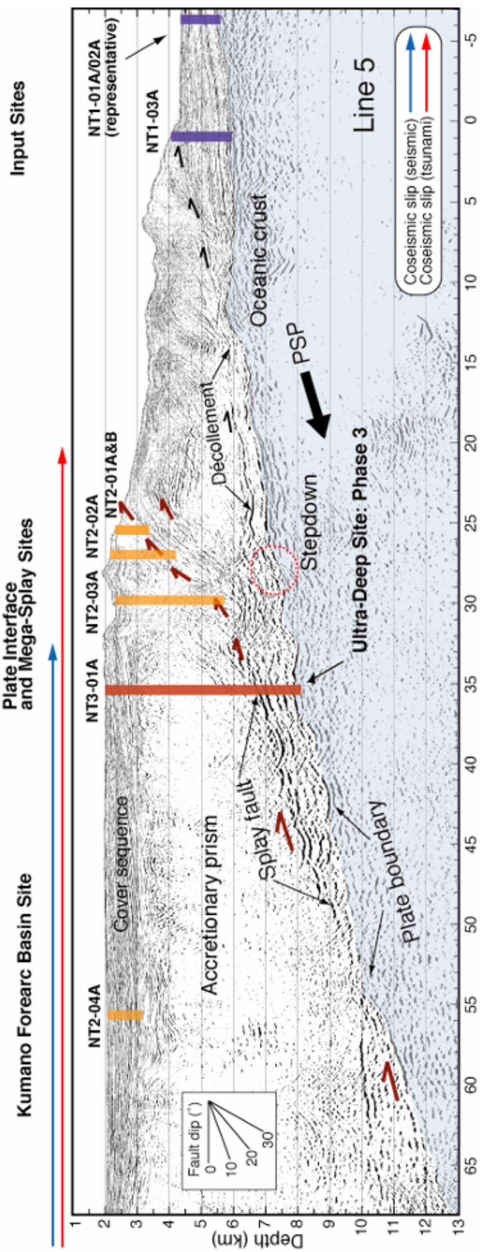

Fig. 7. Cross section of the planned drilling in to the Nankai meagthrust by the NanTroSEIZE project. The profile shows the Kii/Kumano plate interface, accretionary prism, Kumano basin, prominent splay fault system, the 1944 Tonankai estimated coseismic slip (red line), and the décollement stepdown to the top of the oceanic basement (orange dotted circle. Proposed drill sites are in some cases projected to this line (after http://ees.nmt.edu/NanTroSEIZE/).

4 Concluding Remarks: Targets for Future Drilling

We outlined above possible topics and approaches for future drilling into active faults as guided by experience and estimated need. Actual sites for future drilling projects are not proposed here, as we believe that future targets will be developed by interested and motivated groups according to opportunities that change with time, place and scientific interest. As an illustration for this process, one may use the 1994 meeting on scientific drilling in which Zoback and Emmermann (1994) listed five to seven attractive sites for drilling into active faults. Only one site (SAFOD was already in preparation in 1994) on this list has materialized to become a drilling project.

We hope that the second decade of drilling into active faults will use the experience, knowledge and enthusiasm in the scientific community to surpass the exciting achievements of the first decade.

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Hotspot Volcanoes and Large Igneous Provinces

Donald J. DePaolo[1] and Dominique Weis[2]

[1]Department of Earth and Planetary Science
University of California, Berkeley, CA 94720-4767, USA
e-mail: depaolo@eps.berkeley.edu (corresponding author)

[2]Department of Earth and Ocean Sciences
University of British Columbia, Vancouver, BC V6T 1Z4, Canada

Abstract

Ocean island volcanoes and large igneous provinces, both of which represent mantle plume volcanism, are attractive drilling targets because of compelling scientific issues, the layered structure of lava accumulations, and the demonstrated capability to retrieve a high percentage of core in many environments. Although the programs supporting on-land scientific drilling — ICDP, and in the U.S., NSF-Continental Dynamics — are nominally about continental drilling, the primary dichotomy is between on-land drilling and ship-based offshore drilling (IODP). Mantle plume volcanic rocks are accessible to on-land drilling in many oceanic settings as well as on continents. Drilling and coring ordered, datable sequences of lavas can address questions about the mechanisms of magma generation and transport, the geochemical and geophysical structure of mantle plumes and their relationship to the structure and composition of the deep mantle, the structural evolution of large volcanoes, the subsidence history of volcanic piles, the flexural properties of the lithosphere, and the hydrology, alteration history and geobiology of subsurface volcanic environments.

1 Introduction

Hotspot, or mantle plume, volcanism is one of the major processes affecting the interior of the Earth. Mantle plumes may be the primary mechanism of heat loss for the Earth's core and are also one of the primary driving factors in plate movements. Plume heads are influential in forming and modifying plate boundaries, while plume tails and their surface tracks constitute major features of the Earth's lithosphere (e.g., Richards et al. 1989;

Duncan 1991). The influence of mantle plumes, and the large lava accumulations that are associated with them, on continent formation and evolution constitutes a continuing theme of the science of continental dynamics (e.g., Hill et al. 1992).

Non-hotspot related volcanism on the Earth is produced in conjunction with plate tectonic processes. Examples are the new oceanic crust formed at mid-ocean ridges, the linear volcanic chains associated with subduction zones, and the relatively small volumes of lava associated with continental extension (Fig. 1). The magma supply for non-hotspot volcanoes is thought to come from melting of the uppermost mantle, so the geochemistry and petrology of non-hotspot lavas tell us mainly about the composition of the upper mantle and processes that occur there. One great attraction of mantle plume volcanoes, from a petrological and geochemical standpoint, is that the mantle plume that produces them may have originated in the lower mantle, most models suggesting that the strongest plumes originate from near the core-mantle boundary (Morgan 1971, Christensen 1984; Hansen and Yuen 1988; Van Keken 1997; Jellinek and Manga 2002). Mantle plumes are consequently messengers from the deepest levels of the silicate part of the Earth (DePaolo and Manga 2003; Brandon et al. 1998). Mechanisms leading to volcanism on other planets in the solar system, such as Mars and Venus, are believed to closely resemble the processes responsible for terrestrial hotspot volcanism (Kiefer and Hager 1991).

Although the programs supporting on-land scientific drilling — ICDP, and in the U.S., NSF's Continental Dynamics — are nominally about continental drilling, the primary dichotomy in terms of drilling technology and logistics is between on-land and ship-based offshore drilling (IODP). Hence drilling in both continental large igneous provinces (LIPs) and in oceanic hotspot islands has come under the auspices of the continental drilling programs. The reasons for drilling oceanic islands and LIPs revolve around scientific issues in geochemistry, petrology, volcanology, geodynamics, biology, and hydrology. The research questions in mantle geochemistry, petrology and volcanology have been the primary impetus, but unanticipated results relating to biology, hydrology and geodynamics have come from the drilling that has been already carried out; for example, in Hawaii (DePaolo et al. 1996, 2001b; Stolper et al. 1996).

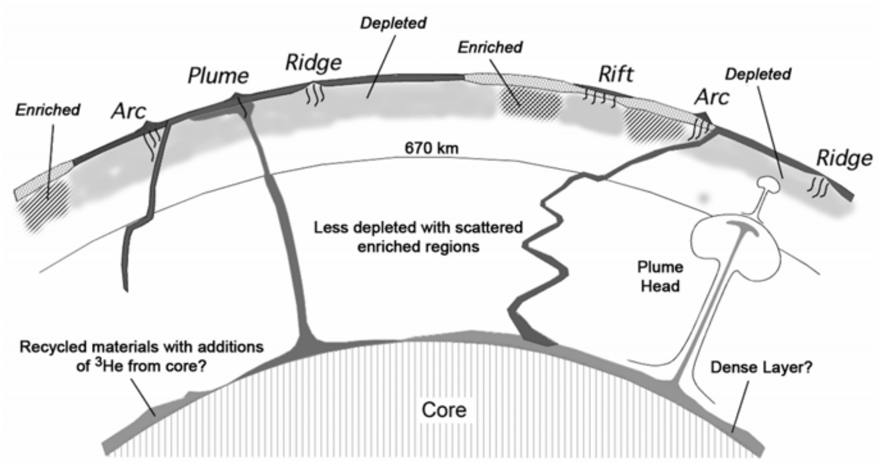

Fig. 1. Schematic cross section of the Earth's mantle, core and crust showing the spatial distribution of various mantle reservoirs with specific element and isotopic geochemistry. Depleted and enriched designation refers to incompatible trace elements with reference to an idealized "bulk mantle" composition. Most types of volcanism (mid-ocean ridge, island arc, continental margin arc, and continental rift) involve melting of the uppermost upper mantle. Hot spot volcanism, especially for the larger plumes, such as Hawaii and Iceland, may be the only case where the melting involves mantle that has recently ascended from much deeper in the Earth. The sources of plumes are shown here as being near the core-mantle boundary, or from a large plume head in the mid-mantle. There is current debate about whether plumes come from the core-mantle boundary region, and if they do, whether they come from the core-mantle boundary itself, or from just above an intrinsically dense layer mantling the core. There is also debate about whether the mantle at the core-mantle boundary is a primordial layer that is billions of years old, or composed of recycled oceanic lithosphere that has been exposed to the ocean and atmosphere relatively recently.

An important characteristic of ocean islands and LIPs makes them attractive for drilling: the volcanic accumulations are made of subhorizontally stacked lava and pyroclastic sequences, some as much as 5 to 10 km in thickness, all arranged in chronological order. Drilling intersects the primary structure at a high angle and hence a maximum amount of information can be gained through drilling. Experience from the Hawaii Scientific Drilling Project (HSDP) shows that subaerial lava sequences can generally be cored efficiently, with penetration rates of 25 to 40 m/day. Submarine hyaloclastite is also easy drilling. Submarine lavas are more difficult to drill because the fractured pillows result in slow penetration rates (5–15 m/day) and hole stability problems. HSDP has also shown that it is possible to choose drill sites where few intrusive rocks are encountered, long stratigraphically-continuous sequences can be cored, and both the lavas and pyroclastic rocks are unaltered by post-eruption processes. The clearest justification for drilling volcanic sequences exists for young lavas from active or recently active volcanoes where the magmatism can be studied in the geodynamic context in which it was generated. Young volcanic sequences are also least subject to dissection by erosion, and thus only drilling can access the deeper levels of the lava piles. A major challenge for studying young basalt lavas is obtaining precise ages for the lavas (geochronology), but in higher-K lavas this may be less of a problem (e.g., Sharp et al. 1996, 2005).

2 Hotspots: Mantle Chemistry to Lithosphere Dynamics

2.1 Mantle Geochemistry

Models for the structure of the mantle continue to evolve but are not easily testable (Fig. 1; cf. Zindler and Hart 1986; Hofmann and White 1982; Hofmann 2003). Particular interest is now focused on the core-mantle boundary region and the lowermost mantle. If mantle plumes sample this area, then detailed studies of plume-related volcanic rocks are one of the few ways to characterize the geochemistry of the deepest mantle. The mantle plume model for hotspot volcanoes has recently come under attack (Foulger et al. 2002), but is still the best explanation for quasi-stationary intense volcanism far from plate boundaries (Davaille 2003; DePaolo and Manga 2003), large volumes of oceanic plateaus and large igneous provinces (Richards et al. 1989), and the different geochemical characteristics of OIBs and MORBs (e.g., Hofmann 2003). The objective for the future is to better characterize the internal geochemical and petrological structure of plumes to get more information about the deepest parts of the mantle (Bryce et al. 2005). Systematic drilling on ocean island hot spots and in LIPs may be the only way to get the necessary information.

Large igneous provinces are thought to result when a new plume, originally generated at the core-mantle boundary, arrives under the lithosphere and begins to melt (Griffiths and Campbell 1990). The explanation for the large amount of lava (ca. 10^6 km^3) erupted in a short time (about 10^6 yr) is that a large volume of anomalously hot mantle enters the depth range where melting can occur (from about 80 to 180 km) in a short time. An essential result of the numerical models of mantle plumes (Farnetani et al. 2002) is that the part of the plume that melts to produce lava comes almost exclusively from the very bottom of the mantle — within 25 to 50 km of the basal compositional boundary — which can be either the surface of the outer core or the top of a dense silicate layer mantling the core. The volcanic rocks produced therefore represent the only sampling that is possible of this critical boundary layer in the Earth. Answers to questions such as the degree to which the core and mantle are in chemical communication (Jeanloz 1993; Brandon et al. 1998), whether the base of the mantle is a graveyard for subducted slabs (Hofmann and White 1982), and even questions such as when the core formed and the age of the Earth relative to meteorites (see Boyet and Carlson 2005) may be locked in the lavas of hotspots and LIPs.

A more detailed schematic of plume melting and magma transport under Hawaii and other long-lived oceanic hotspots associated with plume "tails" is shown diagrammatically in Fig. 2. Much like in the models of Farnetani et al. (2002), the only part of the plume that melts is the hot central core, and this plume material must come from a thermal boundary layer at or near the base of the mantle. Hawaiian volcanoes, however, because they sit on a moving oceanic plate, systematically sample across the melting area of the plume as they grow. In the 1 to 1.5 million years it takes them to grow, a volcano drifts about 100 to 150 km across the plume and hence samples first one side, then the middle, and then the other side of the melting region. This "scan" of the plume top provides information on the detailed structure of the lowermost 25-50 km of the mantle, all laid out in sequence in the lavas of individual volcanoes, and accessible only by drilling.

An example of the information that can be extracted from the systematic sampling associated with a continuous lava sequence is shown in Fig. 3. The $^{3}He/^{4}He$ ratio of the HSDP lavas increases systematically down core, and the ratios also become more variable (Kurz et al. 2004). The deeper lavas are also older, so the data succession down core is also an age progression, and, according to the model of Fig. 2, a "scan" over the plume. The results suggest that the central part of the plume has high $^{3}He/^{4}He$, whereas the periphery of the plume has lower $^{3}He/^{4}He$ similar to mid-ocean ridge lavas. The high ^{3}He signal is interpreted to be associated with the base of the mantle. This characteristic is compatible with the basal layer of the mantle being primordial material but is not easily reconciled with the basal layer being recycled subducted oceanic crust. The narrowness of the ^{3}He signal suggests that it is confined to the central part of the melting region, which in turn is confined to the central part of the plume (Bryce et al. 2005). The ^{3}He-rich material must therefore come from within perhaps 10 km of the base of the mantle, which suggests that perhaps the ^{3}He is coming from the core. Figure 3b shows that the high-^{3}He lavas also have high ^{208}Pb, and together these characteristics are similar to lavas from the young submarine volcano Loihi, which must now be close to where magma derived from the core of the plume is reaching the surface.

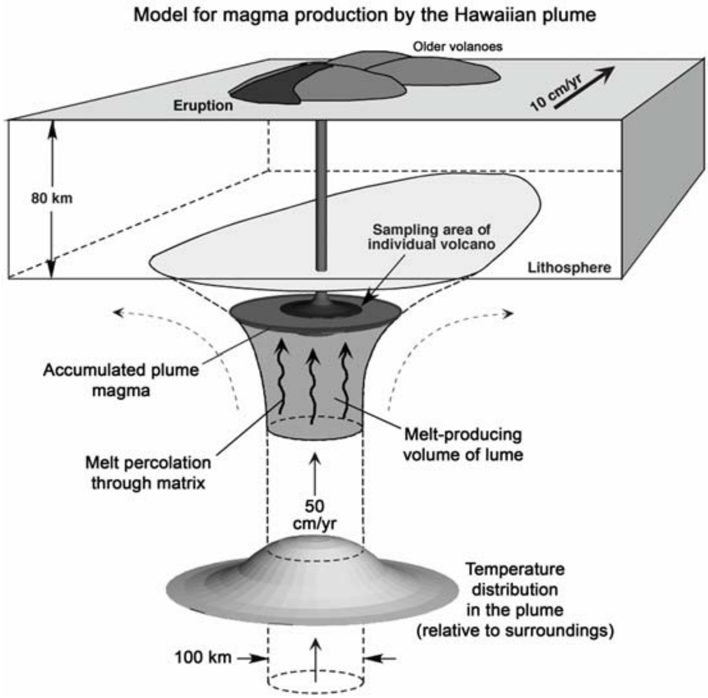

Fig. 2. A simplified model for magma production in the Hawaiian plume showing how a lava sequence can be related to the thermal and chemical structure of a plume. The Hawaiian volcanoes drift slowly over the melt-producing region of the plume during their 1 to 1.5 million-year active lifetimes. The magma supplied to an individual volcano probably comes from only a fraction of the area of the melt-producing region, so the volcano's "sampling area" sweeps over the plume as the volcano grows. The melt, as it percolates upward within the melting volume of the plume, also samples vertical heterogeneity in the plume. Ordered sequences of lavas, such as those recovered by the Hawaii Scientific Drilling Project, represent a systematic sampling of the vertical and radial structure of the plume. For Hawaii, the part of the plume that is hot enough to melt is only the central core due to the thick lithosphere. In other hot spots, where the lithosphere is thinner, a larger fraction of the plume melts. Similar models may apply to flood basalts, and analyses of the lavas recovered from coring are a unique and systematic record of the melting processes and magma source structure.

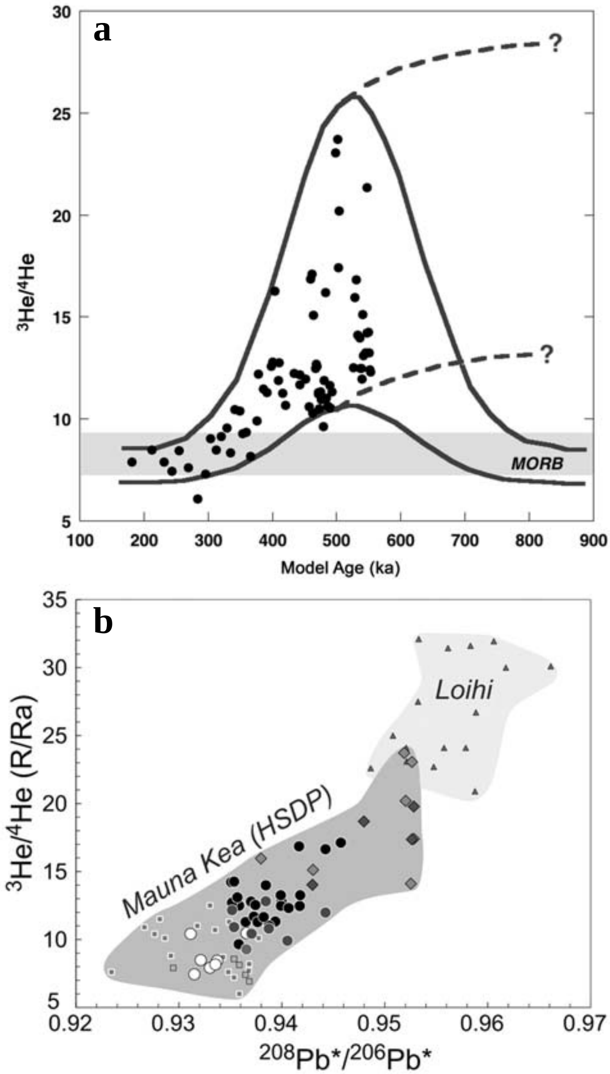

Fig. 3. a. Helium isotopic ratios measured in HSDP lavas versus age (Kurz et al. 2003). Age in this case comes from the model of DePaolo and Stolper (1996). There is a very large change in the helium isotopic character of the lavas through the HSDP section. The high $^3He/^4He$ ratios are associated with the Earth's deep mantle and may come from the core-mantle boundary region. One model here shows what would be expected for a radially-zoned plume; the other shows what an asymmetric plume might look like. **b.** Helium isotope ratios plotted against ^{208}Pb, showing that samples from the deepest levels of the HSDP2 core approach the isotopic compositions of lavas from Loihi (Eisele et al. 2003).

The Hawaii example is one of the simplest in terms of geodynamics. Models for many other hotspots (e.g., Galapagos, Azores, Tahiti) need to be more complex because the movement of the lithosphere relative to the plume has changed with time. Iceland is yet another example, where the plume comes up at a ridge so that much more of the plume melts and hence the lavas provide information on a thicker vertical section of the base of the mantle (Ito et al. 2003). Kerguelen is yet a different case, because initially the plume activity was associated with continental breakup and a ridge environment, and then it evolved into an intraplate environment, moving farther and farther from a ridge with time (e.g., Frey et al. 2000; Weis et al. 2002; Weis and Frey 2002).

2.2 Volcanology

The internal structure of large oceanic volcanoes is still a matter of considerable debate because little direct information is available. It is inferred that the volcanoes start out as steep-sided cones of pillow basalt on the ocean floor. Once they breach the ocean surface, they should evolve to a 3-layer structure, including subaerial lavas on top, a large apron of volcaniclastic material, and the pillow-lava seamount at the center. The thickness of each layer depends on seafloor depth and subsidence during volcano growth, and the presence or absence of volcanic rift zones. The proportion of intrusive rocks making up the interior of large volcanoes is also unknown but subject to much speculation (Walker 1990). The HSDP data confirm the 3-layer model (although less hyaloclastite was found than expected; Figs. 4 and 5), but indicate that some estimates of the amount of intrusive rock are far too high.

The growth rate of hot spot volcanoes is also important information. Geodynamic models that give the temperature and upward velocity as a function of position in the plume, combined with petrological models for mantle melting, yield estimates for the amount of magma produced in the plume per unit time. Magma production should be at maximum above the axis of the plume and drop off systematically with radial distance away from the plume axis (Watson and McKenzie 1988; Ribe and Christensen 1999; DePaolo and Stolper 1996). The overall eruption rate of the volcanoes is related to this magma production rate, but it is not certain what fraction of the produced magma is actually erupted and/or intruded into the volcanic edifice. The Ar-Ar dates obtained on the HSDP core (Fig. 6a) provide the first detailed picture of the growth history of a large oceanic volcano over an extended time interval. The measured ages can be accounted for roughly with a simple model for the magma production in the plume (DePaolo and Stolper 1996; Figure 6b), but these measures are far greater than had been estimated based on dating of surface outcrops and dredged submarine lavas (Moore and Clague 1992).

For Kerguelen, as a contrasting example, an overall 5 degree dip from west to east allows for sampling different lava compositions, from tholeiitic to alkaline as age decreases over many millions of years (Nicolaysen et al. 2000). The age and composition progression corresponds with changes in the type of magma source, which is analogous to Hawaii, but on a much longer time scale. The early stages of the building of the island on the Northern Kerguelen Plateau indicate influence from a depleted mid-ocean ridge-type reservoir, with the source of magmatism being along the southeast Indian Ridge (SEIR) (Weis and Frey 2002). Comparison of various oceanic settings with different compositions will lead to a better understanding of oceanic volcano structure.

2.3 Hydrology, Microbiology, and Alteration

The subsurface hydrology of oceanic islands is largely unknown, even though there have been simple, general models for a long time. One unexpected feature of the HSDP drill site is the low temperatures that extend to great depth (Fig. 7). The temperature profile requires that cold seawater (and/or deeply penetrating groundwater) be circulating through the volcanic pile, even at depths grater than 3 km (Thomas et al. 1996; Kontny et al. 2003). A unique feature of core from oceanic islands is that it allows for understanding both alteration of basalt glass and the activity of microorganisms as they develop progressively with time and temperature (Walton et al. 2004). Most other situations require study of samples with unknown temperature history, or do not preserve the stages of progressive alteration and infection that can be observed, for example, in the HSDP core. The alteration process may be significant in understanding the reactions and compositional exchange between seawater and basalt glass at low temperatures, providing an analogue system for the early history of fluids that circulate through mid-ocean hydrothermal systems and that lead to significant ore deposit formation. Evidence of traces of microbiota may help document the extent, abundance, and level of organic activity in the subsurface (Fig. 8).

Fig. 4. Examples of rock cored by the HSDP. The upper picture is a portion of a fresh aa flow interior. In the center is "hyaloclastite" or volcanic sediment, and lower is pillow basalt. At all levels of the HSDP core, fresh volcanic rocks were recovered.

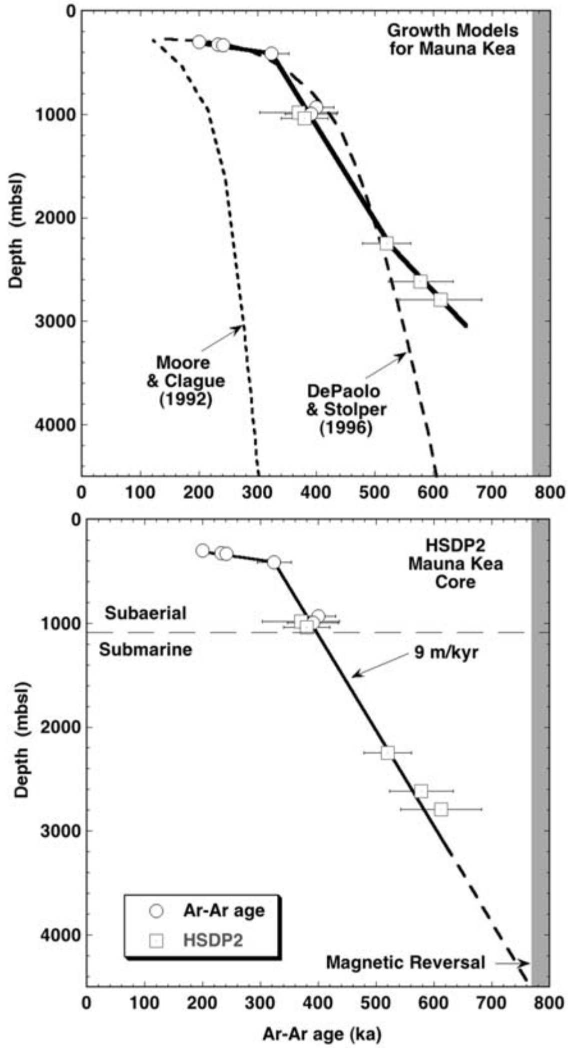

Fig. 5. Age versus depth for Mauna Kea lavas from the HSDP core. The age information is critical for reconstructing the position of Mauna Kea in the past relative to the hot spot, and allows the geochemical data to be related to three-dimensional structure in the plume. The data are also important because they show for the first time how long the volcanoes take to grow. Simple models for the volcano growth from plume magmatism (DePaolo and Stolper 1996) reproduce the observations only moderately well. The constant accumulation rate from 600 to 320 ka is not predicted, although the age data have sufficient uncertainty to allow for the predicted decreasing accumulation rate with time. Previous models published prior to drilling (e.g., Moore and Clague 1992) had suggested that Mauna Kea was only about half the age that it is.

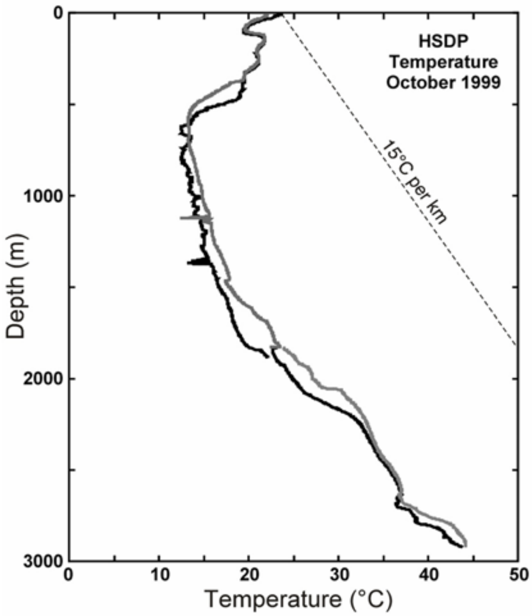

Fig. 6. Temperature versus depth in the HSDP well measured about 1 month after cessation of drilling in 1999. A geothermal gradient of 15°C per kilometer might be expected for a lithosphere of about 90 km thickness with a basal temperature of 1350°C. The observed temperatures are much lower, although a gradient close to the expected is present below about 2000 m depth. The anomalously low temperatures are believed to be due to rapid circulation of cold seawater through the basalt pile. Radiocarbon ages of saline water pumped from the well at about 800 m depth confirm the relatively rapid flow of a seawater-like fluid through the volcanic rocks (Thomas et al. 1996). In the upper 300 m of the well, the cooling is due to freshwater aquifers. The discovery by HSDP of significant fresh groundwater resources within the volcano is of considerable interest for water resources on all of the Hawaiian Islands.

2.4 Magmatic Processes

Ocean island volcanism constitutes a fertile test bed for models of the generation and transport of magma from the mantle. Even for the simplest models of axisymmetric plumes, there is considerable uncertainty about the depth and extent of melting, the role of water and mineralogical heterogeneity, the percolation of magma through the melting zone, and the transport of the magma to the volcano's shallow plumbing system. The growth rate of volcanoes gives information on the temperatures, upwelling velocities, and melt generation rates in the mantle (Ribe and Christensen

1999). The petrological and geochemical characteristics of the lavas tell us about depth of melting, extent of melting, residual minerals in the melting region, and crystallization processes in the magma en route to the surface. Isotopic characteristics help to constrain the source characteristics of the mantle plume, the contributions of various components, and the size and composition of heterogeneities.

Studies of Hawaii, Iceland, and other hotspot lavas continue to yield new insights into magma generation processes and their relation to geodynamic models, mantle composition and heterogeneity (e.g., Hauri 1996; Norman and Garcia 1999; Stolper et al. 2005; Kincaid and Hall 2005). The extended, ordered sequences of lavas that can be obtained by drilling are a unique resource for estimating the length and time scales of magmatic processes and source characteristics (DePaolo 1996; Eisele et al. 2003; Blichert-Toft et al. 2003; Haskins and Garcia 2004).

2.5 Lithosphere Dynamics

Although lithosphere flexure has been studied for decades, there is still a far from complete understanding of the effective thickness and rheology of oceanic lithosphere (Watts 2001). Flexure models are critical for understanding the subsurface volumes of oceanic volcanoes (Moore 1987), and hence the relationship between volcano volume and magma production in the mantle plume. Unique information on subsidence and flexure can be obtained while recovering lava samples for petrological analysis. In Hawaiian volcanoes, for example, the subaerial-submarine transition is typically within 1.5 km of the surface (e.g., Fig. 4), and thus is accessible by drilling through the subaerial lavas — the part of the lava section that can be cored most efficiently. The depth to the subaerial-submarine transition, combined with geochronological study of the lavas (Fig. 9), provides firm data for evaluation of lithosphere flexure models (Sharp et al. 1996; DePaolo et al. 2001a). In Kerguelen, most of the lavas have been erupted subaerially, and only for the oldest ones in the NKP, 34 Ma old, is there evidence for submarine eruption (Weis and Frey 2002). Drilling on the Kerguelen Archipelago itself would allow for a comparison with Hawaii and for a better understanding of what controls the submarine-subaerial transition and the depth of eruption.

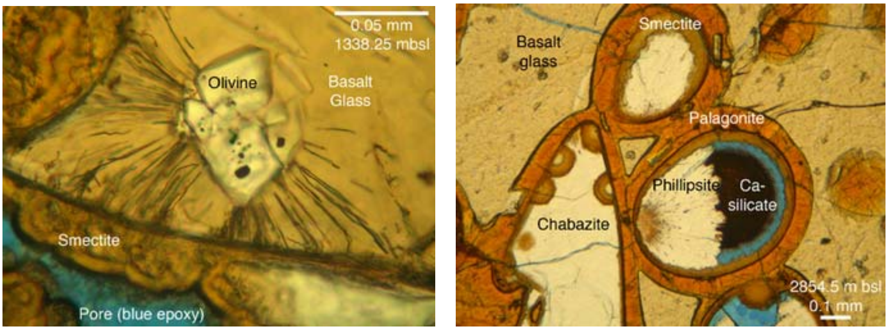

Fig. 7. Alteration features and mineralogy of glass-bearing HSDP samples from 2884 meters below sea level (upper) and 1338 meters below sea level (Walton and Schiffman 2004). A systematic change in mineralogy is found with depth and temperature. Some of the features are thought to be due to micro-organisms living at depths up to about 1500 meters.

3 Large Igneous Provinces in Earth History

Episodic events punctuate Earth history, and large-volume mafic magmatism resulting from processes other than 'normal' seafloor spreading and subduction constitute a major class of episodic phenomena (e.g., Coffin and Eldholm 2000; Stein and Hofmann 1994). Such magmatism results in the formation of large igneous provinces (LIPs), which comprise continental flood basalts, volcanic rifted margins, oceanic plateaus, ocean basin flood basalts, submarine ridges, ocean islands, and seamount chains (e.g., Mahoney and Coffin 1997). LIPs have the potential to provide important insights into mantle dynamics as well as to have caused significant environmental changes. First-order, frontier problems in LIP research addressable by drilling include:

Do plume heads cause continental breakup (Courtillot et al. 1999)? The majority of Earth's divergent continental margins are characterized by thick sequences of mafic volcanic rock that in some instances correlate temporally with adjacent continental flood basalts (Fig. 10). Although there is a distinct correlation, it is not yet understood how anomalously warm and/or upwelling mantle can thermo-mechanically erode the lithosphere and create weak zones susceptible to rifting. An alternative view is that plate divergence is responsible for instigating decompression melting of the mantle, although this should not necessarily produce the large volume of erupted magma observed in many LIPs. Understanding the precise temporal and spatial relationships between tectonics and magmatism via complementary geological (including key drilling), geophysical, and modeling investigations will contribute to addressing this issue.

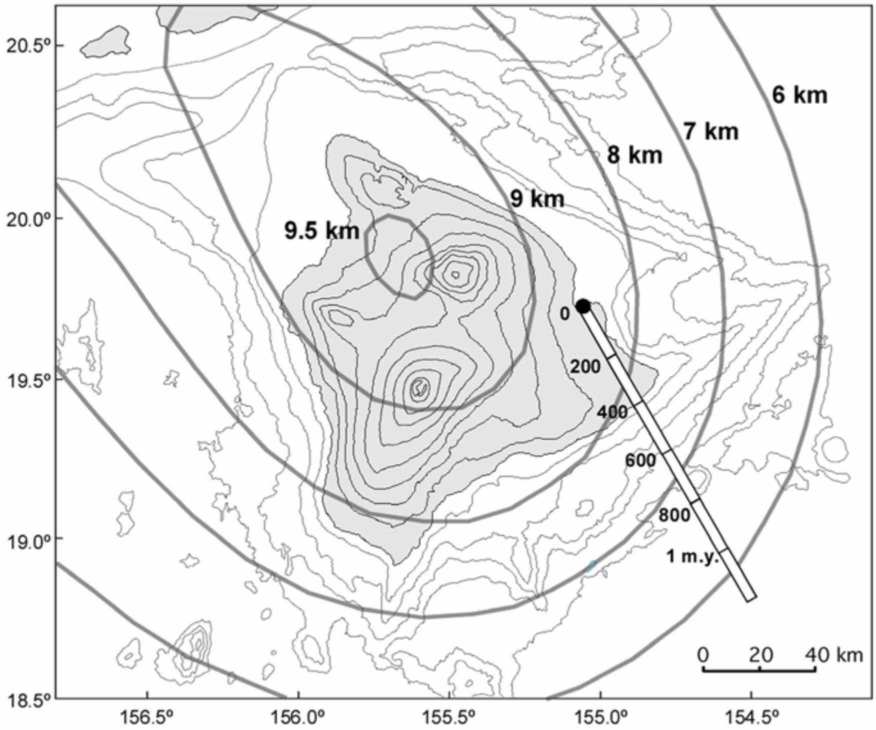

Fig. 8. Estimated contours of depth to the old ocean floor under Hawaii based on lithosphere loading and flexure models (Watts and TenBrink 1988). At the HSDP site there is a precise datum indicating that there has been 1080 m of subsidence since 400,000 years ago. Shown on the figure is the calculated position of the HSDP site for the past 1.2 million years. This track suggests that there should have been about 700 m of subsidence over the past 400,000 years at the HSDP site if the flexure model is correct. The difference is likely to be due to additional deformation that occurs under the volcanoes. More data of this sort, which can only be obtained by drilling, could provide unique constraints on flexure models.

Extraterrestrial impacts and flood volcanism — can bolide impacts instigate massive mantle melting? Bolides have impacted Earth throughout its history, and earth scientists have focused much attention on the global environmental consequences of extraterrestrial impacts. The effects of impacts on the solid earth, however, have been relatively neglected. Recent studies have suggested that the Siberian flood basalts (Jones et al. 2002) and Ontong Java Plateau (Ingle and Coffin 2004) may have formed as a result decompression melting of the mantle induced by bolide impacts. Scrutiny of LIP rocks and contemporary sedimentary sections recovered by drilling, together with complementary modeling studies, may help to answer this fundamental question.

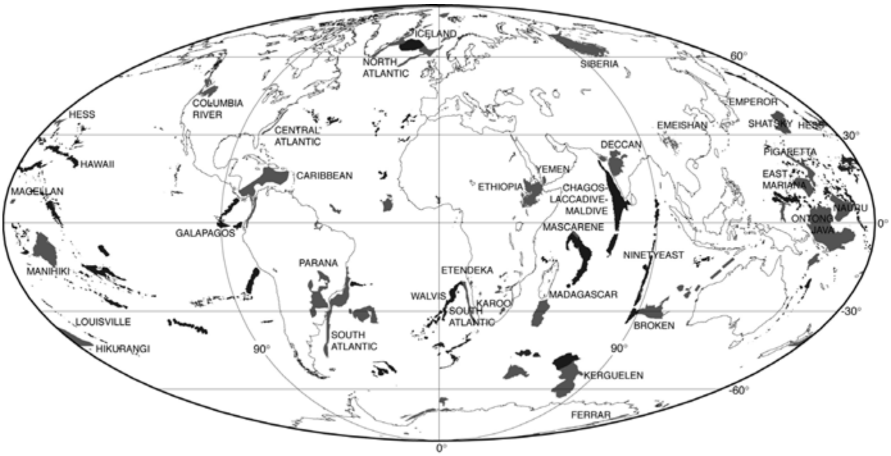

Fig. 9. Global distribution of large igneous provinces (Mahoney and Coffin 1997). Systematic core drilling in most of these provinces could yield important insights into the magma generation process and the nature of the mantle plumes responsible for the volcanism.

Can flood volcanism trigger significant environmental change? Two major mass extinctions of Phanerozoic time, the end-Permian and end-Cretaceous, correlate temporally with emplacement of the Siberian (e.g., Campbell et al. 1992) and Deccan (e.g., Officer and Drake 1985) flood basalts, respectively. Courtillot and Renne (2003) provide evidence for a correlation between the ages of LIPs (CFBs and OPs) and those of mass extinctions and oceanic anoxia events (Fig. 11). Major oceanic anoxic events 1A and 2 correlate temporally with formation of the Ontong Java Plateau (e.g., Larson and Erba 1999) and the Caribbean flood basalts (e.g., Kuroda et al., in prep.), respectively. The Paleocene-Eocene thermal maximum correlates temporally with the peak of Tertiary North Atlantic volcanism (e.g., Eldholm and Thomas 1993; Svensen et al. 2004). Such tantalizing correlations suggest causal relationships; however, copious analyses of drilled basalts and syn-sedimentary sections, as well as much-improved models of environmental change induced by solid earth processes, are required to understand these relationships (Wignall 2001; Courtillot and Renne 2003).

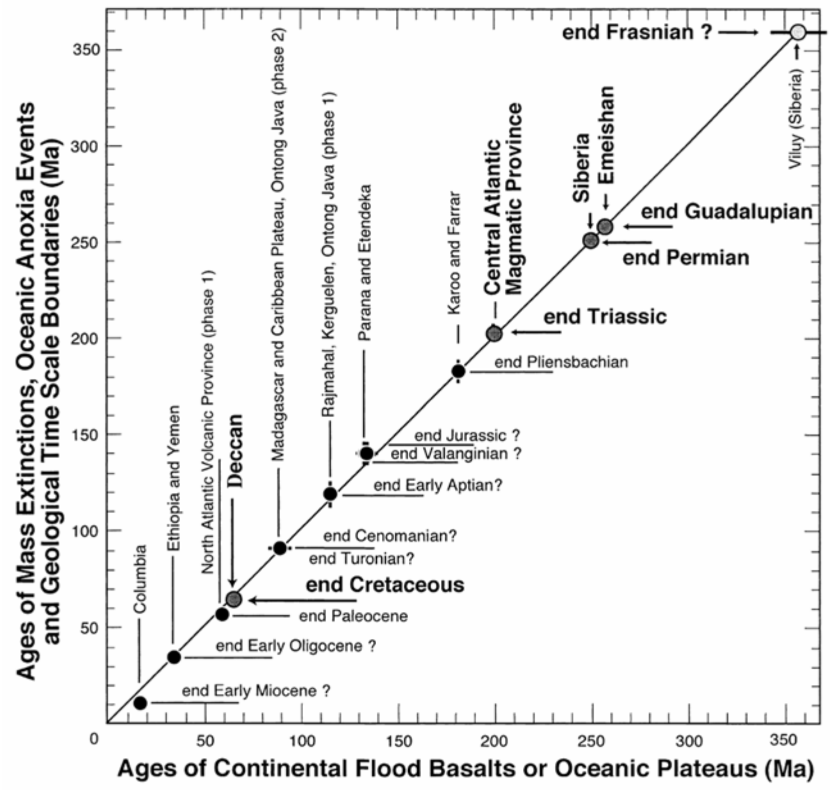

Fig. 10. Correlation between the ages of flood basalt provinces and mass extinctions (all in Ma). The possible causal relationship is still a matter of debate. The figure is taken from Courtillot and Renne (2003).

Many LIPs span the continent-ocean transition (Fig. 10), and cooperative International Continental Drilling Program (ICDP)/Integrated Ocean Drilling Program (IODP) studies will be necessary to advance our understanding of the solid earth and possibly extraterrestrial processes responsible for LIPs and of how intense basaltic volcanism interacts with the atmosphere, hydrosphere, and biosphere.

4 Possible Future Targets for Drilling

4.1 Further Drilling on Oceanic Islands

Although drilling in Hawaii has been successful, it has also raised a number of new questions that could be addressed with targeted drilling elsewhere in Hawaii, and as well as on other oceanic islands. For Hawaii there is evidence that the southwest side of the plume differs from the northeast side (e.g., Abouchami et al. 2005), and there is also evidence that the plume geochemistry changes with time (e.g., Bryce et al. 2005). The Mauna Kea volcano drilled by HSDP shows relatively regular and systematic changes in lava geochemistry with time, but there are larger and less systematic changes that are evident in the available samples from Mauna Loa and Hualalai. Even very shallow drilling in the Koolau volcano has produced unexpected results (Haskins and Garcia 2004). Drilling into the largest volcano in the chain — Haleakala — which also sits at a pronounced change in trend of the island chain, is likely to yield important information about the symmetry and long-term evolution of the Hawaiian plume.

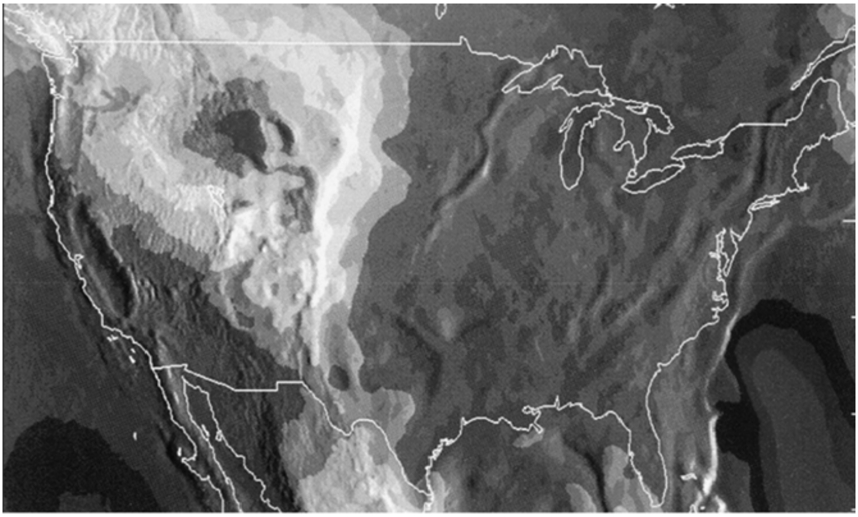

Fig. 11. Geoid map of the continental United States and parts of Canada and Mexico showing the pronounced anomaly centered on the Yellowstone–Snake River Plain area. The Yellowstone region is one of very few examples of an active plume rising under continental lithosphere. Continental drilling results would be enhanced by geophysical imaging of the upper mantle that will be done as part of EarthScope.

Other oceanic volcanoes with different geodynamic contexts would also constitute attractive drilling targets. At present, some of the ocean islands with especially anomalous geochemical characteristics, such as Tristan da Cunha, Reunion, St. Helena, and Samoa, are treated as being equivalent in importance to Hawaii and Iceland (e.g., Zindler and Hart 1986; Hart et al.

2000). Drilling into these islands would be worthwhile to determine if the anomalous geochemistry persists in lavas from deeper in the volcanic piles. It would also be of interest to evaluate the subsidence histories of volcanoes built on oceanic crust of different ages, as well as their hydrology, magmatic processes and biogeochemistry.

Successful drilling on many oceanic islands may not be as easy as in Hawaii. As an example, the rotary drilling done on Reunion in 1985 (Rancon et al. 1989) was able to recover cuttings of only 1 km of stacked lava even though a 3 km hole was drilled. At about 1 km depth the hole entered a region of mostly intrusive rock, which persisted to the bottom of the hole. This experience apparently results from the drilling having been done near the volcano summit, although it was unavoidable due to the subsidence of the island (and the original objective of the drilling; which was geothermal exploration). Under the summit region there is a much higher likelihood of encountering intrusive rocks as well as hydrothermal alteration. For comparison, the Grand Brule drill hole on Piton de la Fournaise was located about 10 km from the summit caldera and encountered mostly intrusives at 1000 m depth whereas the HSDP drill hole was located about 40 km from the summit of Mauna Kea and encountered no significant intrusive bodies down to a depth of 3335 m.

4.2 Snake River Plain

The Snake River Plain (SRP) of southern Idaho has long been associated with the concept of a hot-spot (mantle plume) track which links voluminous flood basalts of the Miocene Columbia River province to Quaternary volcanic centers at Island Park and Yellowstone (Craig 1993). The plume track is marked by a series of rhyolitic eruptive centers that signal the arrival of the hot-spot beneath a new crustal location followed by extensive eruptions of basalts. Existing drill holes in the ESRP show that the basaltic carapace ranges from less than 100 m to over 1000 m thick, with rhyolite basement extending to depths in excess of 3000 m. The plume model has been questioned by recent studies which suggest that these features may be explained by localized asthenospheric upwelling associated with edge effects of North American plate motion and the descending Farallon slab (e.g., Humphreys and Dueker 1994; Humphreys et al. 2000), but the plume model still remains viable for explaining the Cenozoic evolution of western North America, especially considering the large positive geoid anomaly associated with the Yellowstone plateau (Fig. 12).

Core drilling in the Snake River Plain would be timely because it would complement EarthScope-sponsored geophysical studies of continental lithosphere in the northwestern U.S. (USArray and the Plate Boundary Observatory). A systematic series of shallow to intermediate depth drill holes taken along the axis of the Snake River Plain could help test models for the origin and evolution of alleged “plume-related volcanism.” Core samples would also allow for examination of the relationships between rhyolites and basalts, while a series of holes would allow comparison of coeval lavas erupted at different locations along the “plume track.” Drill holes in the SRP could also be instrumented with continuous recording strainmeters and seismometers as part of the PBO and would provide ground-truth observations for crustal and lithospheric studies by the USArray.

Drilling in the Snake River Plain would also be useful for evaluating models of plume-lithosphere interaction. Physical models of plume tail dynamics in continental domains are controversial. Sleep (1990) proposed that topographic relief on the hotspot swell (500 m to 1000 m for Yellowstone) was due entirely to thermal buoyancy. This model predicts that a mantle plume would flatten and spread when confined beneath continental lithosphere, causing a broad circular uplift that would be deformed into a topographic parabola by interaction with the moving lithosphere (Smith and Braile 1994). In contrast, Saltzer and Humphreys (1997) calculate that 20% to 100% of the topographic swell could be compositionally driven, as a result of depletion of the underlying asthenosphere. This implies that no thermal plume is needed to support the observed topographic and geoid swells. Drilling into the SRP basalts would provide critical petrological, geochronological, structural and geochemical data for assessing the plume model and the role of the lithosphere.

4.3 Kerguelen

The Kerguelen mantle plume has been active for at least 120 Myr. The Kerguelen Archipelago is the third largest oceanic island after Hawaii and Iceland and represents part of the Cenozoic volcanic activity of the Kerguelen plume (e.g., Weis et al. 2002). Spreading along the Southeast Indian Ridge (SEIR) over the past ~40 Myr has progressively increased the distance between the SEIR axis and the Kerguelen hotspot; as the ridge moved to the northeast relative to the hotspot, the hotspot evolved from a ridge-centered position to an intraplate location (i.e., Iceland-like to Hawaii-like) (Fig. 13). Field studies of volcanic sections on the archipelago indicate a clear geographic, temporal and compositional trend from the NW tholeiitic-transitional series to the SE alkaline series (Fig. 14). This trend also corresponds to variation in degree of partial melting, magma supply and plume-ridge interaction.

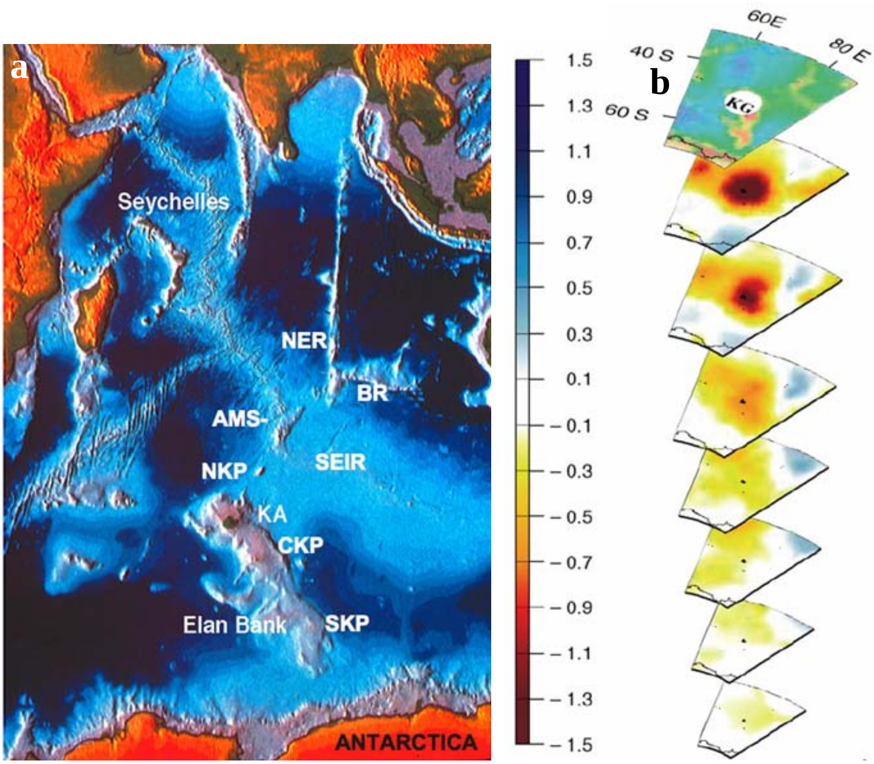

Fig. 12. a. Bathymetric map of the southwestern Indian Ocean indicating the major tectonic features related to the Kerguelen mantle plume volcanism. **b.** The vertical section of p-wave velocity perturbation indicates that the Kerguelen Plume can be imaged all the way down to the core-mantle boundary (Montelli et al. 2004). The color scale for velocity perturbations extends from blue (+1.5% velocity contrast) to red (-1.5% velocity contrast).

Drilling on Kerguelen, although logistically demanding, could lead to extensive new insight into plume processes, mantle structure and magma dynamics. Kerguelen apparently preserves both an initial plume-head phase as well as a subsequent long-lived plume tail phase (Fig. 13b). In addition, the volcanic activity has occurred on sequentially older and older oceanic crust. To fully investigate this unique locality will require both an ICDP sponsored project to study the Archipelago, and an IODP sponsored project to study the submarine plateau. This is a rare opportunity to compare plume head and stem volcanism over a time period of 120 Myr.

There are a number of important specific questions that could be answered with drilling at Kerguelen. The magmatic evolution of this province has extended over an extremely long time, especially in comparison to the younger Hawaiian islands for example, and may reveal quite substantial differences with other islands. One straightforward question is how long it has taken for the archipelago flood basalt, covering 85% of the subaerial surface, to form? If the time scale is long enough, there is a possibility that the lavas record the early stage when the Kerguelen Archipelago was coincident with the SEIR at 40 Ma. In a manner vaguely similar to individual Hawaiian volcanoes, the volcanism in Kerguelen has evolved over a long time from mainly tholeiitic to mainly alkalic in composition (e.g., Scoates et al. 2006). However, at present this transition is observed from spatially diverse sections in a NW-SE trend and may be due more to location than age. The tholeiite-alkali basalt transition in Hawaii is clearly related to the plume structure and composition, and the difference in scale at Kerguelen could be highly instructive.

The Kerguelen region lies within the broad expanse of southern ocean territory that is identified with the so-called DUPAL anomaly (Zindler and Hart 1986). This region appears to be underlain in the lower mantle with a region of relatively low seismic velocities (Romanowicz and Gung 2002), which in turn may be the signature of hotter or more geochemically diverse mantle. The Kerguelen lavas, especially because of the longevity of the volcanism, could hold unique clues about the significance of the large scale geochemical structure of the lower mantle, as well as about how plume geochemistry is affected by interaction with mid-ocean ridge mantle and about the role of recycling ancient subcontinental lithospheric mantle or sediments in mantle heterogeneity (e.g., Escrig et al. 2004; Hanan et al. 2004).

Drilling continental flood basalt provinces on-land, such as Deccan, the Siberian traps, Ethiopia or the Parana-Etendeka, might appear easier in terms of logistics but, because of the interactions between the ascending magma and the continental crust, the geochemistry of these lavas is often complicated. Establishing the geochemical signature of the mantle source is therefore more difficult. Nevertheless, continental flood basalt provinces constitute potentially rich natural laboratories for the study of a major class of basaltic volcanism, and limited drill core has already been used in some cases for the study of these lavas (Lightfoot et al. 1993).

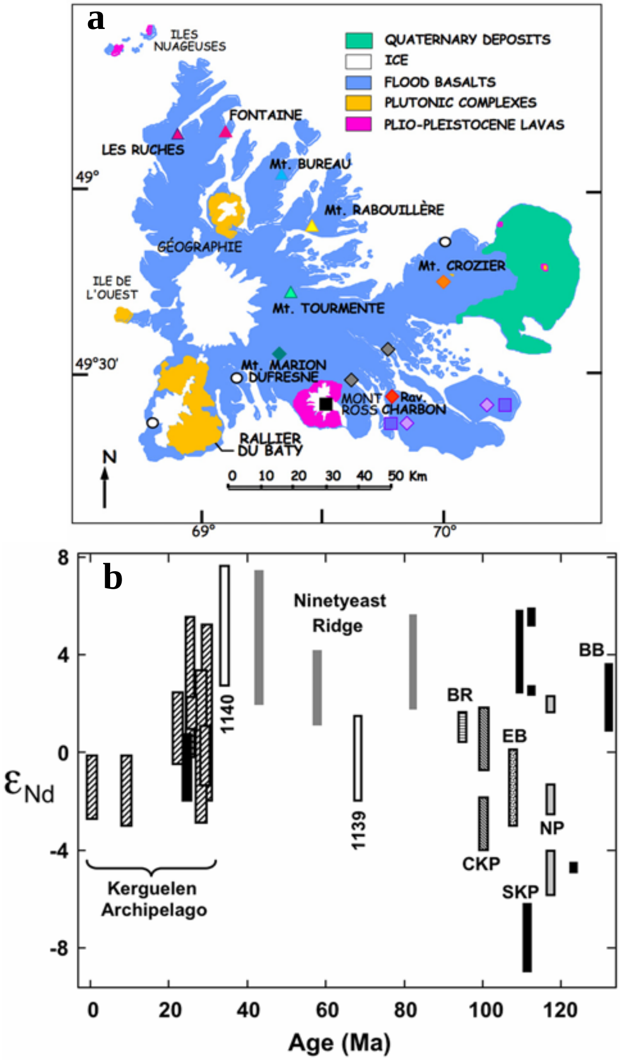

Fig. 13. a. Geological sketch map of the Kerguelen Archipelago. The overall age and composition trend is from 30 Ma tholeiitic basalts in the NW part of the archipelago to 24 Ma alkali basalts in the SE Province. **b.** Age vs. εNd plot shows that the lavas exhibit a large range in isotopic composition, which includes sampling of heterogeneous mantle as well contamination by continental basement that underlies the lava pile and probably is residual from the breakup of Gondwana in the early stages of the Kerguelen plume activity. Kerguelen Archipelago lavas (< 30 Ma) show more limited variations, reflecting mixing between the enriched Kerguelen plume composition and depleted compositions (e.g., NKP, Site 1140, Weis and Frey 2002).

5 Summary and Conclusions

Hot spot volcanic islands and large igneous provinces are attractive targets for continental (on-land) drilling. The volcanic formations are nearly horizontally layered in most cases and drilling allows for the collection of systematic, stratigraphically controlled samples that provide unique records of magmatic processes and mantle structure, lithosphere dynamics, and the thermal, diagenetic, hydrological, and microbiological evolution of the subsurface volcanic environment. Experience with drilling in Hawaii shows that nearly complete core recovery is possible, that penetration rates are reasonably high in many volcanic rocks, and that drilling sites can be identified where the rocks are unaltered and where there are few intrusive rocks. The data that can be obtained by drilling are necessary for developing and testing the next generation of models of mantle magmatism. One of the most important considerations is that the mantle melting under hot spots and LIPs may have come from near the base of the mantle, and therefore the lavas provide geochemical information about the deep Earth that cannot be obtained from any other source. Improvements in geochronology increasingly allow for detailed tests of the relationship between LIPs and other global events, and provide input for new models of hotspot volcano growth and lithosphere deformation. Drilling on oceanic islands also provides unique information on groundwater and seawater aquifers in the basalts, temperature distributions, chemical alteration, and biological activity in the deep subsurface.

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Convergent Plate Boundaries and Collision Zones

Jan H. Behrmann[1], Jingsui Yang[2], and the CoZone Working Group*

[1]IFM-GEOMAR, Wischhofstr. 1-3, 24148 Kiel, Germany
e-mail: jbehrmann@ifm-geomar.de (corresponding author)

[2]Institute of Geology, Chinese Academy of Geological Sciences, 26 Baiwanzhuang Road, Beijing 100037, China

Abstract

Within the framework of the International Continental Drilling Program (ICDP) we propose a comprehensive initiative to drill the continental crust bordering modern and ancient convergent and collisional plate boundaries. These zones host the vast majority of modern megacities and industrial installations on Planet Earth, and at the same time are loci of major earthquakes, tsunamis, volcanic eruptions and other associated great natural threats to human life and to economies. In-depth understanding of dynamic Earthprocesses at convergent and collisional plate boundaries is not possible without scientific drilling embedded into integrated research programmes.

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*CoZone Working Group is: Marco Bohnhoff (GFZ Potsdam, Potsdam, Germany), Andrea Förster (GFZ Potsdam, Potsdam, Germany), Ulrich A. Glasmacher (MPI Kernphysik, Heidelberg, Germany), Jan Golonka (AGH University of Science and Technology, Kraków, Poland), Roy Hyndman (Geological Survey of Canada, Sidney B.C., Canada), Christopher Juhlin (Uppsala University, Uppsala, Sweden), Yrjö Kähkönen (University of Helsinki, Helsinki, Finland), Achim J. Kopf (RCOM, Bremen, Germany), Ilmo Kukkonen (Geological Survey of Finland, Espoo, Finland), Marek Lewandowski (Polska Akademia Nauk, Warszawa, Poland), Jason McKenna (Southern Methodist University, Dallas, U.S.A.), Roland Oberhänsli (Universität Potsdam, Potsdam, Germany), Julian A. Pearce (Cardiff University, Cardiff, UK), Victoria Pease (Stockholm University, Stockholm, Sweden), Paul T. Robinson (Dalhousie University, Halifax, Canada), Hiroshi Sato (University of Tokyo, Tokyo, Japan), Robert J. Stern (University of Texas, Dallas, U.S.A.), Tetsuro Urabe (University of Tokyo, Tokyo, Japan), Kelin Wang (Geological Survey of Canada, Sidney B.C., Canada)

The set of scientific questions identified here is rooted in the plate tectonic paradigm of a dynamic Earth. Proposed studies derived from these questions target on (1) the dynamics of active subduction and collision zones, with focus on the seismogenic zone at the plate interface, and the distribution of deformation and seismicity in general, (2) the role of mantle plumes in orogeny, (3) supra-subduction magmatism in arc systems, (4) the geological manifestation of deep subduction and exhumation of the lithosphere, and (5) aspects relating to continental birth and growth through Earth history. ICDP drilling in convergent and collisional plate margins faces unprecedented challenges regarding drilling technology, drilling depth and requirements for long-term monitoring of Earth processes in downhole observatories.

1 Introduction: The Role of Future ICDP Drilling

Continental crust is formed, deformed, and destroyed at convergent plate margins and collision zones. Subduction of plates at convergent margins is one of the most fundamental geological processes happening on Earth that contributes, in a long run, to continental growth and magmatic accretion in island arcs and, in places, to continental erosion. Subduction zones are complex, dynamic systems in which the thermal, hydraulic, and mechanical properties of the converging plates rapidly evolve in time and space. It is believed that most of the downwelling in Earth’s large scale mantle convection system takes place at subduction zones.

There, one of the most life-threatening geological phenomena occurs: huge earthquakes on subduction megathrusts, including the 2004 Sumatra-Andaman earthquake (M 9.0, with the associated devastating tsunami), the 1960 Southern Chile earthquake (M 9.5), the 1964 Alaska earthquake (M 9.2), and the 1923 Kanto earthquake (M 7.9) that destroyed Tokyo, the capital of Japan. Accompanying geohazards include tsunamis, landslides, powerful volcanic eruptions, and other threats to human life, infrastructure and economies, and to ecosystems. Given that 60% of Earth's population lives within the frontal 50 km of the coast, there is a strong need for scientific and economic efforts, to shed light on the processes responsible for such ocean margin geohazards as well as their mitigation. Scientific drilling has a high potential for such studies and must be an integral and indispensable part of this effort.

Subduction and collision zones are loci of large differential movements at rates of centimeters per year or tens of kilometers per million years, and on the scale of hundreds of kilometers, with very large vertical components. Although the role of subduction in the transport of oceanic lithosphere back to the Earth´s mantle is fully appreciated in plate tectonic theory, the fate and kinematic history of rocks that were carried down to great depths but were later brought back to the surface is not well understood. The phenomenon is known since tectonic melanges were recognized as parts of fossil subduction complexes. Large size blocks or rock belts containing high-pressure or ultra-high-pressure metamorphic assemblages are viewed as resulting from differential exhumation, either driven by buoyancy forces or by upward flow in a confined subduction channel. This concept was later extended to include ductile extrusion of large, hot rock masses in zones of continental collision, and the exhumation of continental rocks having undergone deep subduction and ultra-high-pressure metamorphism in orogenic belts in general. Drilling is essential to create the base of information necessary to advance understanding of material flow and mass budgets in these zones.

A major “deep time issue“ related to subduction and collision processes lies in the old (Meso-Paleozoic and Precambrian) orogenic belts on Earth. How were continental shields being born and is the process continuing, and how do they amalgamate to form terrane collages, continents and supercontinents? While modern convergent and collisional margins are capable of yielding a wealth of “real time“ information on plate dynamics and mountain building, only the study of fossil orogens provides us with a picture of the deeper structural levels of such orogens, as required to understand how orogens evolve with time. Scientific drilling can provide a four-dimensional record of these processes, and is indispensable in the ground-truthing of geophysical measurements and observations.

Productive future research of these active geological processes by means of drilling will require comprehensive programs of coring and other sampling, of downhole measurement and experiments, and long-term monitoring. Thus, scientific drilling does not only open opportunities for encountering rocks by core sampling, but also offers new and challenging possibilities for the *in situ* and *in vivo* study of processes in the subsurface. Some of the features of interest at convergent plate boundaries and in collision zones are temperature, coupled thermo-hydraulic processes, seismicity, stress/strain, and hydrogeological parameters including pore pressure, permeability and hydrochemistry. The latter two require the performance of well testing experiments (e.g., pumping tests) and downhole fluid sampling.

The study of subduction and collision zones has always played a fundamental role in understanding plate tectonics. Among all active zones of convergence on Earth, the active continental margins, where the oceanic lithosphere is subducted beneath continental and arc lithosphere, have the greatest scientific potential for ICDP.

2 Key Scientific Questions

Many fundamental problems in the understanding the dynamics of the Earth System, its natural history and evolution can only be addressed by study of convergent plate margins and collision zones. Key scientific questions deal mostly with aspects of deformation, stress/strain, rheology of Earth materials, solid and fluid mass budgets and transfer. In most cases these aspects cannot be treated independently. The list below, we think, provides a comprehensive, but not exclusive listing of most of the outstanding problems:

- The mechanics of plate motion,
- Rheology of Earth materials,
- Stress field, kinematics and time scale of deformation,
- Strain localization and strain rate gradients,
- Topography building in response to changes in driving forces and lithosphere rheology (especially thermal structure),
- Exhumation of high-pressure and ultra-high-pressure metamorphic rocks,
- The role of fluids and melts (volcanism, plutonism etc.) in generation and modification of continental crust,
- Mass transfer budgets and the recycling of crust in modern convergent plate boundaries and collision zones,
- The birth of continents: Dynamics of fossil accretionary and collisional orogens,
- Crustal architecture and calibration of geophysical observations.

Figure 1 provides a geographical overview of the drilling locations and target areas mentioned and discussed in the text below. Any of these present a “world-class-target“ in the sense that fundamental questions can be addressed in an optimal way. Note, however, that this is a list of examples, not an exclusive list. As future developments and modifications to scientific questions to be answered by drilling occur, there will be ongoing new definition of drilling targets.

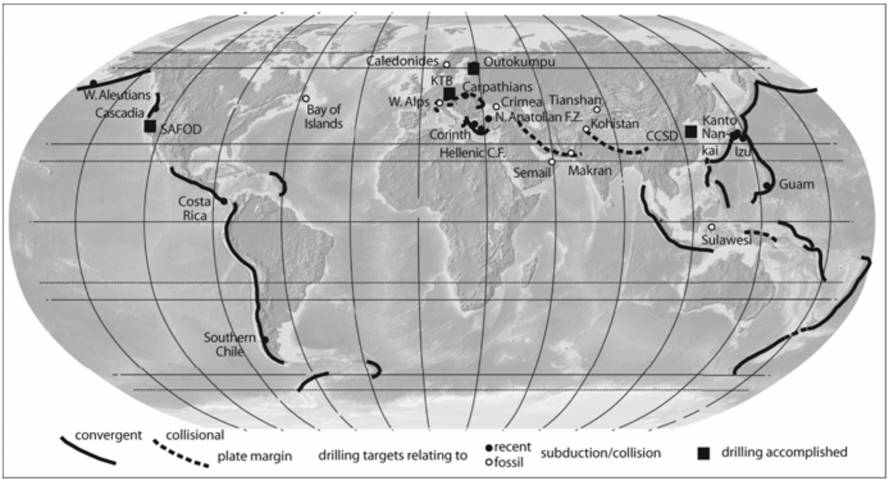

Fig. 1. Map showing distribution of convergent and collisional plate boundaries, accomplished ICDP drilling, and possible drilling targets and areas discussed in the text.

3 Specific Examples of Possible Drilling Targets

3.1 Active Subduction and Collision Zones

3.1.1 The Seismogenic Zone at the Plate Interface

Recently, our understanding on the behavior and nature of subduction megathrusts has been advanced through earthquake observations and seismic profiling (e.g., Shipley et al. 1994; Nedimovic et al. 2003; Bangs et al. 2004; Kodaira et al. 2004). The important new concept is the finding of the "asperity" on subduction megathrusts, based on the analysis of the source mechanism of interplate earthquakes (e.g., Matsuzawa et al. 2002; Yamanaka and Kikuchi 2004). The asperities on a fault surface are the zones that are interpreted to be locked during interseismic periods and generate large amounts of co-seismic slip. For example, Hayakawa et al. (2002) and Fujie et al. (2002) divided seismogenic zone on the subduction mega-thrusts into aseismic and locked parts based on observations at the Japan Trench off the Sanriku coast (Fig. 2). The aseismic part is marked by abundant small magnitude seismic activity with occurrence of repeated earthquakes and strong seismic reflection coefficients from the thrust. On the contrary, the locked part (zone of asperity) is characterized by less small magnitude seismic activity and poor seismic reflection. Close examination of the spatial relationship between the asperity and the reflectivity suggests that the asperity is generated by differences in physical properties along the megathrust plane.

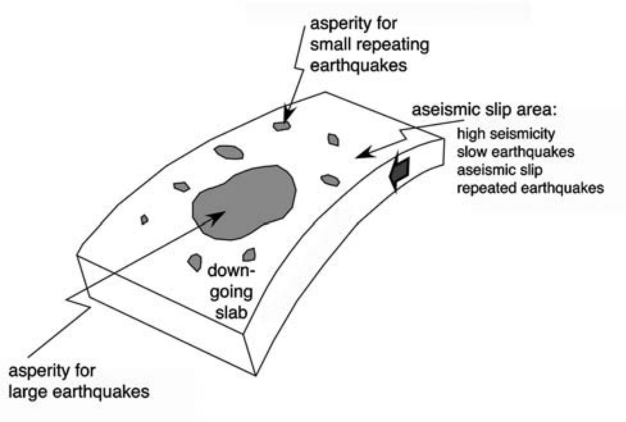

Fig. 2. Schematic diagram showing the distribution and types of asperities on a subduction megathrust, modified after Matsuzawa (2001).

It is suggested that very large inter-plate earthquakes will be initiated by rupture of these asperity patches. In other words, the physical properties of the asperity zones on subduction megathrusts control the behavior of the entire megathrust. However, it is extremely difficult to define or estimate the physical properties of the subduction megathrust from the surface. Besides, it is almost impossible to locate asperities in fossil subduction megathrust structures, and thus the only way for the direct observation of asperities is deep drilling.

Candidate sites for the asperity zone drilling of a subduction megathrust must satisfy the following conditions; a) the depth of the asperity on the subduction megathrust must be shallower than 10 km from a land-based drill site, as this depth seems to be the drillable limit from an engineering point of view, b) the site should be monitored permanently by a network of seismometers, GPS arrays, and other geophysical methods to provide a substantial enhancement of the scientific merits of the drilling, and c) the recurrent megathrust earthquake has to have a large societal impact to justify the cost of drilling. From these criteria, the greater Tokyo metropolitan area (Kanto area; Fig. 1), central Japan, could be the most suitable, although challenging drilling target of this kind in the world. Careful examination of the depths of subduction thrusts elsewhere may also locate other possible sites where the thrust is within drilling depth limits.

The Philippine Sea plate is currently subducting northwestward beneath the Tokyo metropolitan area at a rate of 30-40 mm/yr. Due to the arc-arc collision between the Izu-Bonin-Mariana and Honshu arcs, the Philippine

Sea plate shows an antiformally plunging surface from the Izu peninsula, southwest of Tokyo. Thus the part of the subduction megathrust reached to the surface as an onshore spray fault. The subduction causes megathrust earthquakes, such as the 1703 Genroku earthquake (M8.0) and the 1923 Kanto earthquake (M7.9), which caused more than 105,000 fatalities, mainly due to extensive fires after the main shock. If a recurrent M8 earthquake would occur today beneath the Tokyo metropolitan area, the economic loss may reach to the amount of Japanese annual gross national product (GNP), and trigger a worldwide economic recession. After the Kobe earthquake in 1995 (M7.2) with 6,433 fatalities and 100 billion US dollars economic loss, Japanese islands have been covered by a very dense network of seismic and GPS stations.

Inversion of continuous GPS measurements in the Tokyo metropolitan area has identified an area of slip deficit on the subduction megathrust (Sagiya 2004). This area, which is locked during the present inter-seismic period, represents an asperity patch where a future great earthquake may recur. The co-seismic asperity patches are also revealed by the inversion based on the data of triangulation before and after the 1923 Kanto earthquake and seismic records (Matsu'ura et al. 1980; Wald and Somerville 1995; Kobayashi and Koketsu 2005).

Since 2003, deep seismic profiling has been performed in the Tokyo metropolitan area for the purpose of precise estimation of strong ground motions. The geometry of the subduction megathrust is clearly imaged by four reflection seismic sections down to 25 km in depth (Sato et al. 2005; Fig. 3). By combining the above-mentioned data sets, the asperity patches beneath the Tokyo metropolitan area have been precisely determined. It should be noted that the asperity zone on the subduction megathrust is within the reach of continental scientific drilling. Nevertheless, a deep drilling project into the subduction megathrust named JUDGE (Japanese Ultra-Deep Drilling and Geo-scientific Experiments) project had been proposed since late 80's (Urabe et al. 1997), but the necessity and justification, and drilling requirements of the project are more clearly defined recently with the advance in the research on the subduction zones.

According to the historic records, two large megathrust-earthquakes occurred in 1703 and 1923 in the area and seismic cycles that consist of frequent M7-class-earthquakes before and after the large M8-class-events were observed. Judging from such temporal change in seismic activity, many seismologists agree that in the Kanto region the quiet period in seismic activity probably has gone and we are going to move into a pre-M8 earthquake cycle. We may have certain time to the next M8-class-earthquake, however, we have to start the preparation as soon as possible to be able to monitor the whole seismic cycle using an ICDP deep drill-hole.

Drilling of the subduction megathrust zone is also proposed along the Nankai Trough (Fig. 1) and Costa Rica (Fig. 1) subduction zones within the framework of the Integrated Ocean Drilling Program (IODP). Together with the scientific results from such foregoing projects, we can obtain the comprehensive information about the physical properties of subduction megathrusts at a wider depth range.

The other important contribution of deep drilling into a subduction megathrust is the long term geophysical monitoring of such a structure at depth. In general, fault zones are weak in comparison with their host rocks, thus their behaviour is very sensitive for the changes of stress and strain conditions, and they may act as amplifiers for such changes. Deep drilling projects into the subduction megathrust or seismogenic zone are already proposed as SEIZE experiments to IODP at Nankai Trough (Nantro-SEIZE), SW Japan and Central America (e.g., MARGINS Program Science Plans 2004), including geophysical monitoring. These projects are complementary to each other, and all sites have their own scientific necessity, and specific advantage. The added benefit of a land-based drill hole is to be available for long-term geophysical monitoring, desirably over several decades to cover the whole seismic cycle.

3.1.2 Processes in Active Subduction Zones

Active accretionary, erosional, and related near-trench processes at subduction zones have been targets of many DSDP, ODP, and IODP projects. IODP has now planned to sample and monitor the most seaward part the seismognic zone of the subduction thrust at the Nankai subduction zone through deep drilling. Given the numerous fundamental processes in continental forearc and back arc systems, ICDP also has an important role to play in the study of active margins. Because of the general inaccessibility of most of the research targets by continental boreholes in this environment, the ICDP involvement must be innovative and unconventional. Three aspects of the future ICDP efforts are of particular importance: determination of the thermal and mechanical states of the overriding plate, borehole observatories, and joint land-ocean borehole networks. The principal scientific issues to be addressed are as follows.

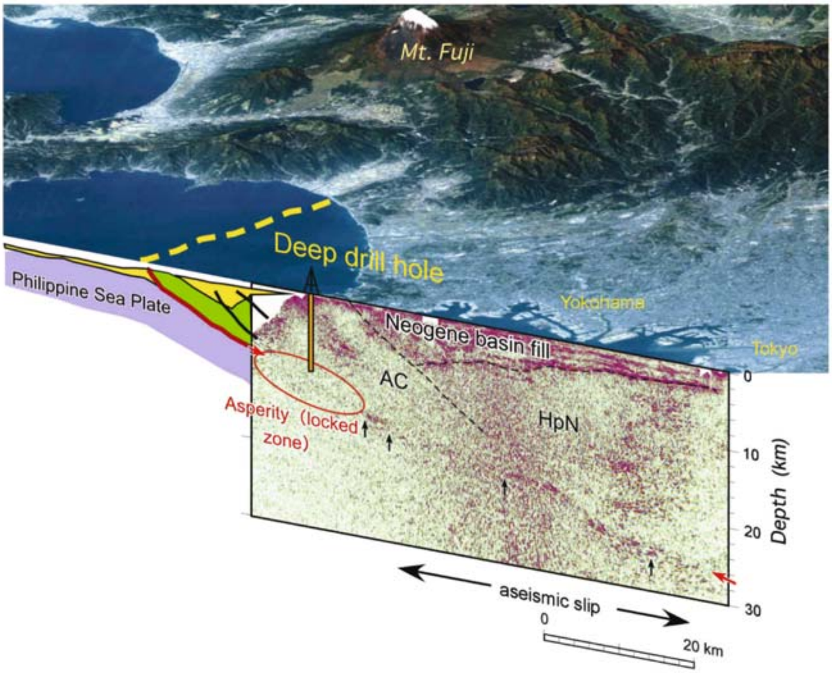

Fig. 3. Proposed deep drilling into the subduction megathrust beneath the Tokyo metropolitan area. Seismic reflection section is after Sato et al. (2005). A zone characterized by low reflectivity of the plate boundary thrust can potentially be reached and sampled by superdeep drilling.

Forearc Thermal Regime. Rock rheology and metamorphic reactions in subduction zones are strongly controlled by the thermal regime, which depends mainly on the age of the incoming plate, convergence rate, and thickness of incoming sediments. The landward limit of the megathrust seismogenic zone may be a thermally controlled downdip transition from velocity-weakening to velocity-strengthening behavior of the plate interface for young and warm slabs, or where the slab is in contact with the hydrated lithospheric mantle of the overriding plate (Hyndman and Wang 1993; Peacock and Hyndman 1999). Thermally controlled depth of brittle-plastic transition and its spatial variation affect the depths of upper plate seismicity and style of long-term forearc deformation. Temperature-controlled slab dehydration facilitates earthquakes in both converging plates, causes serpentinization of the forearc mantle wedge above the slab, and trigger melting, magma production, and hence arc volcanism (Kirby et al. 1996; Peacock and Wang 1999; Hyndman and Peacock 2003).

Despite the importance of the thermal regime in subduction zone dynamics, there have been very few good borehole heat flow measurements in this environment. The most complete land-marine heat flow profiles are probably across the northern Cascadia and the southwest Japan subduction zones. Most of the existing holes are either too shallow for high accuracy or were drilled for industrial purposes and ill suited for precision scientific objectives. There is also a lack of systematic observational quantification of the often large and rapid horizontal transitions between the thermal states of the forearc, arc, and backarc regions. Only through relatively deep (>500 m) drilling and logging at carefully selected sites, measurements of thermal conductivities and rates of radiogenic heat production on drill cores, and correlating with structural and hydrological studies, can we determine the effects of climatic and hydrological perturbations on surface heat flow values, the partition of heat budget between deep-seated processes and contribution from crustal heat production. Only by determining heat flows at multiple sites, can we constrain the spatial changes in heat flow patterns and processes that cause these changes such as mantle flow, melt migration, and frictional heating along the plate interface.

Forearc Stress Regime. Lithospheric stresses, especially those in forearcs, are direct indicators of plate driving forces and mechanical coupling between converging plates (Wang and He 1999). It is important to know how the orientation and magnitude of the stresses change in both the margin-normal and margin-parallel directions, from seaward of the trench to landward of the volcanic arc. Fundamental questions, such as the strength of the subduction fault, the effect of oblique subduction, and the role of mantle wedge flow as a potential basal driving force for the forearc – back arc system, are yet to be fully addressed. But the states of stress of the overriding plate in the forearc environment are not well constrained. One approach is to use fault mechanisms from larger earthquakes or composite mechanisms from smaller events. However, dense networks are required for accurate determination of focal mechanisms of small upper plate earthquakes. These networks exist only in a few forearcs. In addition to regional earthquake data, much of our knowledge of forearc stresses comes from studies of active faults. An important additional approach is through direct borehole observations using techniques such as borehole breakouts and other in-hole measurements that provide information on the orientation and values of stresses. The boreholes must be deep enough to avoid surface effects. Measurements are needed from multiple sites so that comparison with data of very different depth and temporal scales, such as focal mechanisms and fault, motion can be made, where these data are available.

The case for borehole observatories. An important contribution of ICDP boreholes for subduction zone studies is to conduct continuous monitoring of transient changes in geophysical and geochemical parameters related to active subduction processes. Recent geodetic, seismological, and ocean-borehole observations at convergent margins have detected a wide range of tectonic activities that were not known to us previously. These activities provide new challenges and opportunities for ICDP. ICDP borehole monitoring distinguishes itself from seismic and geodetic monitoring by covering a larger depth range and frequency band, and for allowing *in situ* sampling of large volumes of the crust.

Boreholes are needed in the forearc region to monitor seismic and aseismic motion of the megathrust and related crustal deformation. Most great earthquake ruptures have their landward termini beneath the coastal area, where the plate interface behaviour changes from updip seismogenic to downdip stable sliding and, at somewhat greater depth, from frictional to viscous. Coseismic slip of the megathrust may be extremely broadband, generating ground shaking of millisecond periods to excitement of very long-period normal modes of tens of minutes (Stein and Okal 2005). The slip on the thrust may be over seconds (seismic), to minutes (tsunami generation), to weeks or years (slow slip detected geodetically). Postseismic deformation includes afterslip of months to years duration downdip of the rupture zone and long-term viscoelastic relaxation of decades (Melbourne et al. 2002; Wang 2004). The coastal region is by no means dormant during the interseismic period. Elastic shortening of the forearc region is frequently interrupted by “silent slips” on the thrust at the downdip end and beyond the seismogenic zone (Dragert et al. 2001; Ozawa 2002). At the Cascadia subduction zone, such GPS-detected silent slips are closely accompanied by low-frequency seismic tremors (Rogers and Dragert 2003), but the tremors appear to extend into the overlying crust. Crustal strain associated with these motions can be identified with borehole monitoring.

Although shallow-borehole strain meters, such as those being installed by the Plate Boundary Observatory (PBO), are very useful in detecting seismic and aseismic strain changes on land, they are very sensitive to fine-scale structure and rock heterogeneities. At sea, experiments in instrumented ODP and IODP boreholes have shown the value of using fluid pressure observations to constrain tectonic strain pulses (Davis et al. 2001, 2004). These boreholes have hydraulically opening sections communicating with seafloor formations. Volumetric strain changes due to seismic and aseismic tectonic events induce significant changes in formation fluid pressure. A network of pressure-monitoring boreholes may define the pattern of the pressure changes and yields information about the source of the strain events. The poroelastic fluid pressure response “samples” a large rock volume and thus is less sensitive to fine-scale structure and heterogeneities. Recent fluid pressure observations in two near-trench ODP holes at the Nankai subduction zone (Fig. 4) detected a strain pulse correlated with very-low-frequency earthquakes within or beneath the accretionary prism (Davis et al. 2005). On land, fluid pressure monitoring in ICDP boreholes drilled into selected confined aquifers and aquitards in the coastal region will allow the detection of similar strain events across the continental margin and help constrain the spatial extent and frequency contents of their sources.

Broadband seismometers, tilt meters, accelerometers, strain meters, temperature sensors, and fluid samplers in deep boreholes all have been used to detect changes in various geophysical and geochemical parameters associated with subduction processes. Jointly analyzing the temporal and spatial patterns of the changes and correlating with data from seismic and geodetic networks will provide unprecedented constraints to the activities and earthquake and tsunami hazards of active margins. Borehole observatories, especially land-marine profiles across the coast can also be designed to monitor forearc fault systems and volcanic activities.

The case for land-ocean borehole networks. Observation targets at subduction zones, such as the plate thrust interface, are only under a few exceptional circumstances within reach of continental boreholes (i.e., less than 10 km; see above). Large-aperture observation networks that monitor subduction thrust targets and the overlying forearc, from different directions in 2-D and 3-D are thus important; they have the potential to become part of the standard observational infrastructure in subduction zones. Coastal land boreholes and offshore boreholes must be grouped together to form land-ocean profiles or networks. Such a new generation of borehole networks will provide excellent opportunities for correlating signals with other, such as current and planned standard seismic and geodetic networks. Coordinating ICDP drilling and monitoring activities with ocean drilling efforts such as those of the IODP requires innovative planning and execution.

Here we use the Nankai subduction zone, SW Japan, as a case example to illustrate the potential and feasibility of land-ocean borehole networks to monitor the rich variety of transient signals that is becoming evident. The Nankai margin has produced many great earthquakes, often accompanied by distinctive tsunamis. A transect of eight marine boreholes across the seaward part of the subduction thrust, including two deep holes using the Japanese riser drillship technology, has been planned under the IODP project NanTroSEIZE to sample and monitor the seismogenic zone of the subduction fault (http://ees.nmt.edu/NanTroSEIZE/) (Fig. 4). Although drilling will only reach the updip limit of the seismogenic zone, the addition of a number of continental boreholes along the coast will allow the seismogenic zone to be monitored from both ocean and land directions (Fig. 4).

As an example mentioned in the preceding section, fluid pressure transients have recently been detected in existing ODP holes at Nankai. The strain pulses causing these pressure transients indicate ongoing deformation that appears to come from slip near the downdip end of the otherwise locked subduction fault. Further seaward, a large number of very-low-frequency earthquakes also has been detected within or beneath the accretionary prism by a high-sensitivity seismic network on land, also pointing to the activitiy near the updip end of the locked fault (Obara and Ito 2004) (Fig. 4). GPS networks have captured a number of aseismic "silent" slip events that occur within or downdip of the seismogenic zone in this region and many other active margins. Numerous nonvocanic low-frequency seismic tremors occur in the deeper part of the forearc region (Obara 2002) (Fig. 4), possibly related to the dehydration of the downgoing slab. Although accelerometer data at seismic stations suggest strain changes coincident with the tremor activities (Obara et al. 2004), their relation with GPS-detected silent slips has not been established like at the Cascadia subduction zone. All these ongoing geodynamic activities call for a combined land and ocean borehole network to monitor changes in stress, strain, fluid pressure, temperature and fluid chemistry in relation to fault motion and earthquakes.

Other world-class case areas where land-ocean borehole networks would be very useful include Cascadia (Fig. 1), a very well studied typical accretional margin, Costa Rica (Fig. 1), a typical erosional margin, and Southern Chile (Fig. 1), where tectonic accretion and erosion seems to occur intermittently (Behrmann and Kopf 2001). Like Nankai, all these subduction zones have been well surveyed and studied using numerous techniques. Seismic structure onshore and offshore, and geodetic deformation patterns are quite clear. Offshore boreholes exist for tectonic or gas hydrate studies, and a number of these holes have been instrumented and used as observatories. Additional oceanic boreholes have been either planned or proposed. For Cascadia, the NEPTUNE seafloor cable system and the Plate Boundary Observatory (PBO) geodetic network will allow signals to be correlated on a plate scale. At Costa Rica, a borehole transect including land borehole to define the spatial variation of the thermal regime over a short trench-arc distance is both urgently needed and technically feasible.

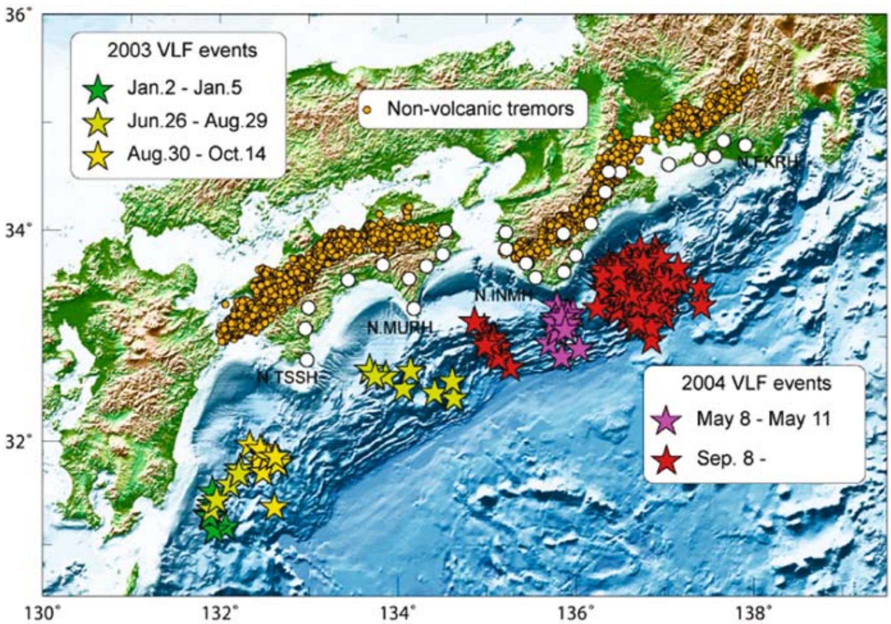

Fig. 4. Nankai Trough subduction zone showing the locations of the planned IODP borehole transect and a possible additional continental borehole transect to form a land-ocean borehole monitoring network. Boreholes are shown as yellow-filled orange circles fill, with the large one showing the approximate planned location of the deepest IODP hole using the riser technology. The three land borehole sites are arbitrarily placed to illustrate the concept. Small brown circles are locations of non-volcanic tremors reported by Obara (2002). Very-low-frequency offshore earthquakes reported by Obara and Ito (2004) are shown as stars color-coded for time of occurrence. Modified from Obara and Ito (2004).

3.1.3 The Hellenic Collision Factory

Given the highly dynamic setting and complexity, collision zones are still poorly understood. In the first ICDP white paper (Zoback and Emmermann 1994), the shortcomings in understanding collision zones as well as the emerging key questions along active plate boundaries have already been identified. Nonetheless, to date no ICDP project has attempted to penetrate and/or instrument a plate boundary fault, or drill a transect of holes across one key collisional margin.

Zoback and Emmermann (1994) have proposed numerous regions for collision zone drilling, including central Japan, the Alps, Himalayas, Marianas, southern Chile, and Greece. We have reviewed this preselection and have discussed it in a wider context, namely based on ongoing activities within other programmes such as marine scientific drilling and observatory science. In recent years, new light has been shed on individual processes with the subduction factory as well as onshore fault and collision zones. However, since many of the processes vary with time (e.g., transient fluid flow, earthquake cyclicity), scientific drilling has started to implement boreholes with observatories capable of monitoring crucial parameters *in situ*. Those initiatives include ICDP-SAFOD (see Fault zone chapter, this volume), IODP- NanTroSEIZE (Nankai Trough Seismogenic Zone Experiment; Tobin et al. 2002), and ocean floor networks such as MARS (Monterey Bay), NEPTUNE (Juan de Fuca plate) or ESONET (European Seafloor Observatory Network).

Among modern collisional settings on Earth, one that covers a very large variety of aspects, and could hence be favoured for a comprehensive large-scale scientific drilling approach: The Hellenic Trench-Backarc (HTB) in the Eastern Mediterranean Sea. It represents a mature subduction zone where African crust is thrust beneath Eurasia, and contains a wide backstop area of partly old accreted strata (marine), occurrence of HP/LT rocks (exhumed on the island of Crete and the Cyclades), an extensional submerged landward forearc (Cretan Sea), and a volcanic arc and backarc basin (Aegean Sea). Furthermore, the HTB hosts the fastest extensional system (Gulf of Corinth) and a major strike-slip zone (North Anatolian Fault Zone, NAFZ) presently representing a large-scale transtensional regime in northwestern Turkey (Marmara Sea). Both domains are earthquake-prone, hazardous geo-environments. The HTB was earlier identified as a promising research target: both, seismic onshore and offshore networks (Harjes et al. 1997; Bohnhoff et al. 2004) and deep-sea cables (e.g., NESTOR) already exist. Observatory science programmes (e.g., EuroCORES, ESONET), which would greatly benefit from ICDP drilling, have already listed the HTB as a prime target for future activities.

Scientific drilling and long-term monitoring in the HTB would be a powerful means to study densely populated areas (megacities like Istanbul and Athens) to minimize societal and environmental dangers, which millenia ago destroyed entire cultures, two of the seven wonders of the world (Colossus of Rhodes 224 BC, Lighthouse on Pharos 365 AD), and several historical sites in the in the circum-Mediterranean.

The HTB retreating convergent margins was capable to generate M>8 earthquakes (365 AD, western Crete, see above) and devastating volcanic eruptions (1650 BC, Santorini) in historic times. Collisional processes which are well recorded over the past ca. 35 million years, including an intermittent stage of micro-continent collision between about 30 and 20 Ma, followed by breakoff of a subducting slab, followed by incipient collision with the passive African margin today. The island of Crete represents a megascopic horst structure developed within the last 5 million years in the central forearc and provides excellent onshore access to the internal structure (Fig. 5).

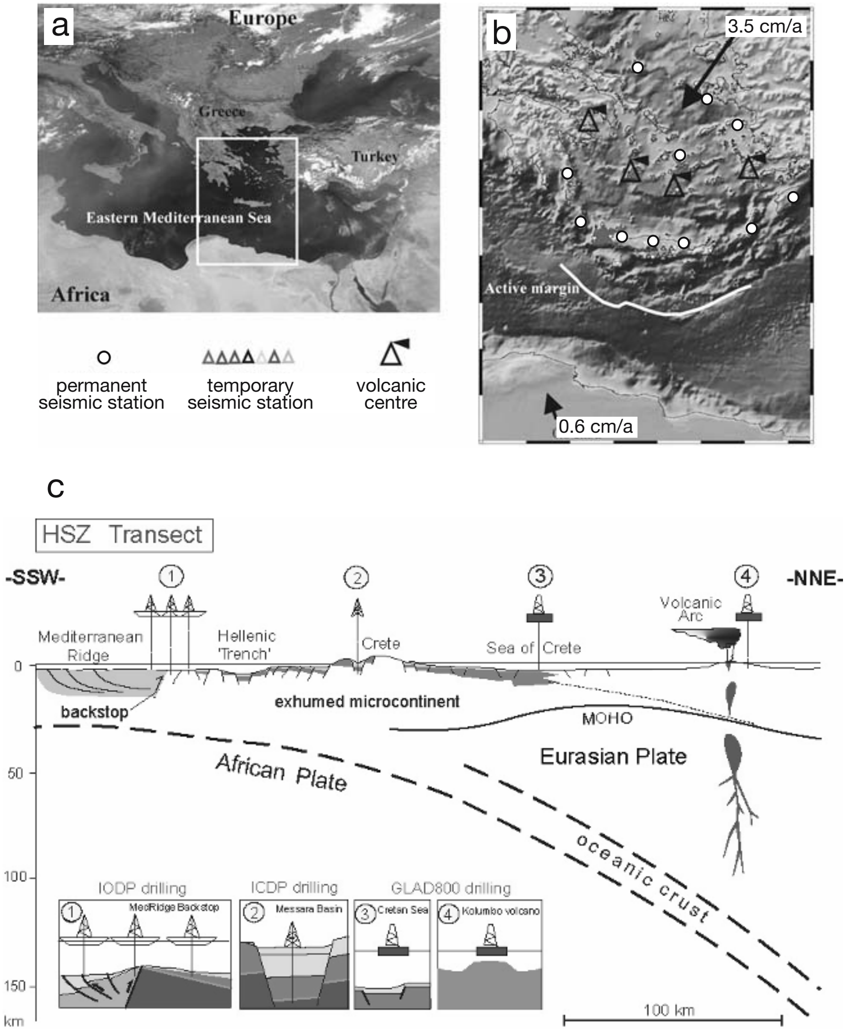

Fig. 5. a. Overview of the Eastern Mediterranean region. The rectangle marks the Hellenic Subduction Zone (HTB) that is enlarged in b. **b.** Overview map of the HTB. Arrows give the GPS-derived horizontal velocity field (simplified, after McClusky et al. 2000) in a Eurasian-fixed framework. Black triangles represent the volcanic centres of Aegina, Milos, Santorini-Kolumbo and Nisyros (from west to east). Triangles and circles mark stations of temporary and permanent seismic networks (Hanka and Kind 1994; Harjes et al. 1997; Bohnhoff et al. 2004), respectively. **c.** Transect of ICDP and marine targets for the investigation of the Hellenic Subduction-Collision Zone.

A combined onshore-offshore programme of scientific drilling and multi-parameter monitoring would address the following key questions:

- How are variations in pore pressure, temperature and stress linked to regional seismogenesis; which of these parameters may act as EQ precursors if monitored in real-time?
- How is the mechanical coupling between the plates achieved, and how are these processes tied into seismogenesis and earthquake magnitude and recurrence time?
- What determines the boundary between contractional and extensional deformation – the „backstop“ geometry, rheology, or both? How do forearc regions N and S of Crete differ mechanically and how is kinematics partitioned in space and time?
- Which are the geometrical pathways of the extensional exhumation of the subducted micro-continent? Can the proposed asymmetric buoyant escape model serve as a general concept for continental growth in retreating subduction zones?
- How is the incipient volcanism in the central magmatic arc related to the transtensional regime, to crustal zones of weakness, and to distinct magma pathways from the Benioff zone towards the surface?
- How is stress partitioned between tectonic faults (contractional as well as extensional) and magmatic processes, and what causes the different pulsation frequencies between micro-earthquakes (t=1 yr) and vertical movements in the volcanic arc (t=10 yr)?

Collision factory drilling is envisaged to contain the following components:

- A land-sea drilling transect through the HTB system to study the Aegean natural tectonic laboratory. This transect comprises a northern (ICDP-driven) and a southern (IODP-driven) domain. After an ICDP workshop on Crete in 1998, proposals for backstop drilling in the Cretan Sea (ICDP), on Crete (ICDP), and in the Mediterranean Sea (IODP) were developed and later combined to form an onshore-offshore deep drilling transect along the HTB (Fig. 5). With moderately deep marine drill sites (ca. 1 km depth) in the backstop region south of Crete, one continental 3-4 km deep drill hole onshore Crete, and further ICDP (GLAD 800) offshore holes within the Cretan Sea (i.e., the forearc-backarc transitional zone) and the volcanic arc (i.e., the submerged Kolumbo volcano as part of the Santorini volcanic complex), a substantial contribution to the understanding of earthquake hazard and mitigation, tectonic evolution and rheology of active collision zones is anticipated. From north to south, the key sites are:

- The Volcanic Arc (proposed ICDP GLAD 800 drilling). A well-developed Benioff zone was identified here by seismological observations to a depth of 150-180 km below the magmatic arc (HVA). The HVA follows the four main volcanic centres of the Hellenic subduction zone (Aegina, Milos, Santorini and Nisyros/Kos, from West to East). The central HVA forms the Cyclades archipelago, a classical example of a high-pressure belt in a back-arc environment (Trotet et al. 2001). Major extensional detachments define metamorphic core complexes (e.g., Lister et al. 1984; Gautier and Brun 1994). Extension was accompanied or alternated with horizontal shortening producing large NE-SW to NNE-SSW trending folds (Avigad et al. 2001) and the Santorini-Amorgos zone of crustal weakness. Here the explosive Santorini volcano (Volcanic Explosivity Index 6.9 or 7.0; Dominey-Howes 2004) is located. The most recent volcanic and seismic activity, however, occurs at the Kolumbo volcanic reef 10 km NE of Santorini, where a new volcanic centre broke the water surface in 1650 AD (e.g., Vougioukalakis et al. 1994). At present Kolumbo is in a state of uplift and its caldera reaches a minimum water depth of 18 m only. We propose to drill into Kolumbos' caldera using the cost-effective GLAD 800 drilling equipment.
- The Cretan Sea (proposed ICDP GLAD 800 drilling). The Cretan Sea represents the northernmost portion of the extensive forearc domain in the HTB, between Crete to the south and the volcanic arc to the north (Fig. 5). Given the small tidal range in the area, shallow GLAD 800 drilling would be feasible in this seismically active, hazard-prone area (Manakou and Tsapanos 2000) to install borehole instruments and a cable for later observatory science. The extensional regime is a critical link between the Cretan drillsite (see below) and the HVA. One of the key aspects here is the remarkable contrast in seismic activity and deep fluid venting north and south of the exhumed Cretan forearc high. Studies here are particularly crucial since the regional stress regime is expected to change: the landward part of the system is decoupled, while the frontal forearc accommodates high basal stresses along the plate boundary fault (the latter causing subduction erosion; Kopf et al. 2003).
- Central Crete ICDP drilling. Crete represents a tectonic window that provides insight into the internal structure and tectonic history of the forearc, and in fact into the deep crustal level. Crete Island formed after a short-lived cycle of subduction, slab breakoff, uplift and thrusting, accompanied by normal faulting within the forearc-high due to exhumation, that way allowing for accretion further south. A rigid stack of nappes formed the continental backstop since about 19 Ma (Thomson et al.

1998), and has since caused very rapid outward growth of the Mediterranean Ridge accretionary margin (Kopf et al. 2003). The major part of the pre-Neogene basement exposed on Crete (comprising the „lower nappes“) is derived from the sedimentary cover of the microcontinent (e.g., Bonneau 1984) that – as a part of the African plate - entered the precursor of the Hellenic subduction zone in the Oligocene/Miocene. High pressure – low temperature metamorphic rocks were exhumed within a very short time span, forming the footwall of a major extensional detachment (Fassoulas et al. 1994) by about 19 Ma (Thomson et al. 1998). Present high seismicity could be linked to a large system of fluid circulation induced by the plate convergence. Some of the fluids contained within the thick sediment cover of the forearc are expelled in mud volcanoes of the accretionary prism (Kopf 2002). Another portion of the fluids within the sediments or in the hydrated upper oceanic crust may be subducted, and trigger strong seismicity at the plate interface. We propose a deep (3-4 km) borehole to study in-situ both the HP-LT history (Kopf et al. 1999) and the source region of micro-earthquake cluster.

- Backstop drilling in the Hellenic forearc (IODP proposal 555-full3). Within ODP (Ocean Drilling Program) and its predecessor DSDP (Deep Sea Drilling Project), several convergent margins have been investigated. However, all these regions have in common that drilling focused entirely on the frontal portion of the forearc prism. In contrast Kopf et al. (1999) proposed to drill a transect of three sites south of the island of Crete from the distal part of the Mediterranean Ridge accretionary prism (MedRidge) across the backstop. Backstops (or mechanical buttresses) to accretionary complexes are among the most important pathways for deep fluid flow processes and define solid material flow within an accretionary prism. Fluid flux at the buttress must influence fluid budgets of the accretionary complex, and earlier work attested that flux rates in the backstop domain exceed those near the toe of the accretionary complex (Kopf et al. 2001). The IODP marine transect aims to illuminate (1) mass and fluid transfer at an accreting convergent margin, (2) the significance of spatial variability of fluids from mineral dehydration and diagenetic alteration at depth, and their interaction with the rock, and (3) their possible effect on seismicity. Each of the three 1km-deep drill holes in the backstop domain will penetrate deep-seated thrusts and backthrust faults and fluids there act as “geochemical windows“ down to several km depth. Fluids will be indicative of enhanced dewatering reactions, and fluid motion possibly cause EQ swarms in the area. Monitoring of fluid-flow and pressure variations would dramatically improve our understanding of fluid budgets and global mass balances, and seismogenesis in accretionary systems.

- A powerful integration of natural laboratory data and observations from the HTB transect is possible with the results from Corinth rift drilling (Fig. 1), and future drilling at the North Anatolian Fault Zone (Fig. 1). This way rifting, transform and thrust regimes, the three natural tectonic expressions of collision, could be interactively studied within the small, well-studied and easily accessible Aegean-Anatolian region. Long-term observatories, both in boreholes and as surface networks, will further address many of the highest priority targets of ICDP and IODP.

3.1.4 The Roots of Arc Systems

Understanding the roots of arc systems is important for a number of scientific and socio-economic reasons: placing constraints on rates and mechanisms for growth of the continental crust; understanding the processes leading to explosive volcanism; and understanding the processes leading to formation of economic ore deposits, such as porphyry copper deposits. We believe that an initial focus should be on juvenile, intra-oceanic arcs (IOA) because these reveal most clearly how arc crust forms and thickens. IOA are also thin enough to targets in deeper parts of the crust to be reached by drilling. These objectives can be reached by drilling in active IOA (e.g., Izu-Bonin-Mariana; W. Aleutians; Tonga-Kermadec) and in fossil IOA (e.g., Talkeetna, Kohistan, Tanzawa).

Modern active seismic sounding is a powerful tool for resolving the arc crustal structure, but this has only been applied to a few IOA. The seismic structure of volcanic arcs is known in only a few locations. Suyehiro et al. (1996) provided the first high-resolution seismic refraction profile through an IOA: the primitive, oceanic Izu arc at 33ºN (Figs. 1, 6). They found that the crust to be about 20 km thick, i.e., thicker than normal oceanic crust. The distinctive feature of this profile is a middle-crustal layer of intermediate (6.0-6.3 km/s) seismic p-wave velocities. It is overlain by an upper crust with velocities up to 5.8 km/s, and overlies a lower crust with velocities of 6.6-7.3 km/s.

The upper crustal layer in the Izu section comprises mainly volcano-sedimentary rocks and minor intrusions. The middle crustal layer may be interpreted as intermediate to felsic plutonic rocks, on the basis that these rocks that have been dredged from the remnant Palau-Kyushu arc and is exposed on land in the Tanzawa Mountains of Japan, where the Izu arc has collided with Honshu. The lower crust in the Izu section actually comprises two sub-layers: one with velocity of 6.6-7.2 km/s, and a deeper layer with a velocity of 7.3 km/s. One interpretation is of mafic cumulates overlying mafic-ultramafic cumulates but the layers could also include granulitic residues from intracrustal melting as well as fragments of pre-existing oceanic lithosphere. It must be appreciated in this context that active magmatic arcs are very dynamic systems, which must continue to evolve as they thicken. Added information in Fig. 6 shows an interpretation (from Stern et al. 2003) of active magmatic processes beneath an IOA that is consistent with the Izu seismic section.

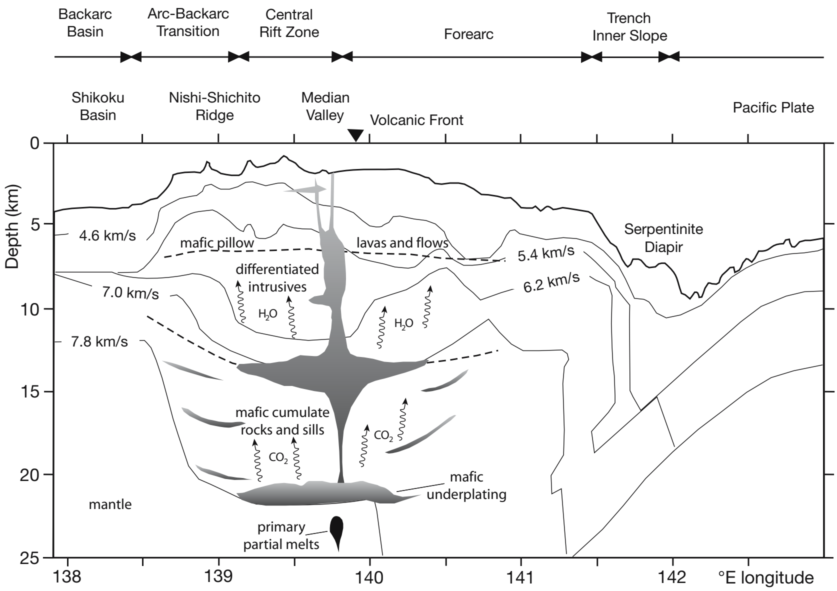

Fig. 6. The seismic section of Suyehiro et al. (1996) across the Izu arc, highlighting the presence of a 'tonalitic layer' in the middle crust resulting from melting and crystallization processes in differentiating magma chambers. Added geological information comes from an interpretative section drawn by Stern (2003) through an intraoceanic arc. Many deep crustal processes are poorly understood and drilling would help to understand arc roots and thus document mechanisms of crustal growth.

Seismic profiles for other IOA differ in detail from this model (Stern 2002). The only other oceanic arc with a comparable seismic profile is the Aleutian Arc with higher density middle crust if compared to the Izu arc, but a lower-density and thicker lower crust. The differences may be explained by tectonic variations between the arcs, or may reflect the fact that the Izu arc has evolved over a shorter time period. Arcs built on continental lithosphere are sometimes referred to as "Andean-type arcs" (ATA). Of these, crust beneath the Cascades (Fig. 1) is thicker (35 km) but otherwise not too dissimilar from the Aleutian section. Andean crust is the second-thickest on Earth (after Tibetan crust) and is up to 70 km thick. Yuan et al. (2000) used teleseismic P-to-S converted phases to image the deep structure of the Andes. They inferred a mid-crustal section characterised by 'dehydration and melting' and a lower crustal section characterised by 'dry refractory crust'. The extent to which ATA and IOA lower crust consists of residue or cumulates is an important unanswered question.

Overall, the objectives in studying arc roots resemble those in studying lower oceanic crust. Key questions include:

- How does arc crust evolve in time from nascent arcs to evolved arcs?
- What is the nature of the magma plumbing system whereby magma fed from the mantle traverses the crust and is delivered to sub-volcanic magma chambers, and what are the associated processes?
- What are the sizes, nature and depths of magma chambers within the arc crust?
- At what depths are volatiles released within the crust and how does this impact melting, fractionation, and mineralization?
- What is the thermal budget of crust and how does this constrain the assimilation and melting of pre-existing crust?
- How do deep crustal processes influence the likelihood of explosive eruptions or mineralization at sub-volcanic levels?
- What is the bulk composition of especially intra-oceanic arcs and what is the role of arcs in crustal growth? How important is delamination of high-density lower crust beneath arcs?
- How does arc crust differentiate as it ages and thickens?
- What is the nature of the Moho beneath arcs? Are there both petrological and seismic Mohos beneath arcs, as is observed for ophiolites and inferred for oceanic crust?

As with oceanic crust, drilling type sections for sampling, analysis and downhole experiments is a key approach for interpreting seismic profiles and understanding the origin and composition of the crust. It may be possible to drill through relatively thin crust of IOA forearc, but not through the crustal welt associated with magmatic arc. Even more so than is the case for much thinner oceanic crust, a single drilled section through typical arc crust to the Moho is currently unrealistic. Scientists studying mid-oceanic ridges overcame this problem by offset drilling – drilling a series of holes through different layers that have been tectonically uplifted until a composite section could be constructed. This is almost certainly the best approach for understanding arc crust. Offset drilling of the deeper parts of oceanic crust has revolutionised our concept of oceanic crustal growth and we believe that drilling arc roots would similarly revolutionise our understanding of the evolution of arc crust. In devising a strategy for studying arc roots by continental drilling, it is our view that the optimal approach is to start by studying simple arc systems of known setting (young, intraoceanic) and subsequently to investigate more complicated targets. Focussing on IOA also provides opportunities for synergistic drilling in co-ordination with IODP.Below we present three important targets for scientific drilling in IOA: Nascent arcs, Middle crust of a Mature Arc, and Lower Crust-Upper Mantle of a Mature Arc.

Drilling Target 1: Nascent arcs. One way to understand arc processes is to drill arcs in their incipient stages of formation, in supra-subduction zone ophiolites and subduction initiation regimes. The advantage of this type of target is that it highlights magma-genetic processes, i.e., it enables the arc to be studied before millions of years of crustal processes modify the crust beyond recognition. Some Supra-Subduction Zone ophiolites record the transition from spreading to subduction. These include parts of the Semail ophiolite in Oman, the Pindos and other ophiolites in Greece and Albania, and the Bay of Islands Ophiolite in Newfoundland (Fig. 1). Some forearc terranes also provide exposures of the earliest arcs, examples being Eua (Tonga), Guam and the Ogasawara Islands. Drilling ophiolites can be done by ICDP alone but drilling nascent arc crust requires close co-ordination with IODP.

Probably the best targets are in the Izu-Bonin-Mariana forearc, where a strong case has been made that Eocene crust is an in situ ophiolite that formed during the initial stages in the formation of a subduction zone (Stern and Bloomer 1992). One attractive locale for drilling is Chichijima and other parts of the Ogasawara islands, the type location for the boninite magma type. The island exposes a boninite volcano built on an edifice of pillow lavas and dyke swarms. Although we do not know the depth to the Moho, the fact that dyke swarms are exposed in the lower parts of the island may indicate that it is feasible to drill through the volcanic edifice and its basement. ODP Leg 125 nearby drilled through the flanks of a boninite volcano into the dyke-swarm of the underlying oceanic crust (Pearce et al. 1992) and could be drilled to greater depth; however, on-land drilling would reach any Moho more cheaply and easily. Another attractive possibility is drilling on Guam, which exposes boninite pillow lavas. A prerequisite for all forearc drilling, however, is a detailed seismic refraction survey and detailed other geophysical and geological data.

Drilling Target 2: Arc Middle Crust. Suitable drilling locations exist where lower sections have been tectonically exposed or exposed by erosion. There are many examples of these in older arcs, notably the Cretaceous Kohistan arc in Pakinstan where a complete arc section is believed to be exposed. However, given the need to place the drill hole in context by understanding the setting of the arc being drilled, the best known at present is the Tanzawa belt in Japan.

The Izu arc terminates in the north against Honshu in the Izu collision zone, a rare example of active arc collision and terrane accretion. Accretion has led to the uplift and exhumation of the roots of the arc in the Tanzawa Mountains. The Tanzawa Plutonic complex likely represents the middle crust of the Izu arc of Upper Miocene (4.7 to 10.7 Ma). The complex has been studied on land where the tonalite suite contains a series of features of interest: cumulate layering, xenoliths, evidence of magma mingling and leucocratic veins. Drilling will provide the core for evaluation of the complex relationships between the components of the middle arc crust, and for testing the hypothesis of Kawate and Arima (1998) that the tonalities formed by amphibolite melting. This crustal section also has the advantage of helping to constrain the Izu arc seismic line (Fig. 6).

Drilling Target 3: Arc Lower Crust and Upper Mantle. Fundamental questions about magmatic processes in the lowermost crust and uppermost mantle beneath mature IOA require the identification of suitable sites for drilling. The Moho of Supra-Subduction Zone ophiolites present one target as they highlight ways in which subduction-derived magma can infiltrate and react with pre-existing oceanic lithosphere. Another type of target is the deep roots of accreted arcs. The Talkeetna terrane of southern Alaska (De Bari and Coleman 1989), which exposes lower crust and upper mantle, may present one of the best such targets, given that the ‘classic’ Kohistan arc in Pakistan lies in a presently politically-unstable region.

3.1.5 Plume-modified Orogens: the Case of the Carpathians

In its western part the Carpathian Orogen (e.g., Kovác et al. 1998) consists of an older unit known as the West Carpathians (WC) and a younger one, known as the Outer Flysch Carpathians (Fig. 1), the latter being overthrusted onto the southern part of the European platform (Cadomian or Hercynian basement). The depth of the cratonic basement in the suture zone, according to the results of the deep seismic (CELEBRATION profile; Guterch et al. 2001), magnetotelluric and magnetic soundings (e.g., Zytko 1997), is below 6-8 km (the basement depth calculated from the platform bending is 10 km). An enigmatic basement uplift exists despite the general southward dip of the European platform under north-western Carpathians that may be caused caused by the geothermal uplift of the asthenosphere, replacing delaminated lithosphere or by mantle plumes, or by basement-involving thrust faults. The boundary between the overriding

WC (Alcapa plate, e.g., Plasienka et al. 1997) and the European plate is the Pieniny Klippen Belt (PKB) The outcropping segment of the PKB is an almost 700 km long, strongly compressed and tectonically complicated suture zone. Here, many questions regarding the evolution of the Central European Alpine system could be answered by drilling. The principal ones are:

- The stuctural position of PKB within Carpathians and its role in the reconstruction of the Cenozoic Alpine system of Europe. The PKB is bounded by first-order strike-slip faults, both, in the North and the South. The deep structure and geometry of the PKB is unknown. Drilling here could help define the nature of the contact zones as well as magnitude and sense of relative displacement between contacting units. It could verify models of the subduction type (A or B) and its direction within the Carpathians, and determine the total thickness of the Lower Miocene deposits in the context of the evolution of the foreland basin. Furthermore, tectonic units buried underneath the Magura Nappes overthrust can be identified, and the palaeogeographic disposition of the PKB basins may be clarified.
- The relationship between geotectonic and geodynamic setting and magmatogenesis. The Outer Flysch Carpathians, adjacent to PKB from the North contains andesitic Neogene volcanic rocks, whose origin is interpreted as a combined effect of the mantle uplift and subduction processes (e.g., Kovac et al. 1998). Here an extensional regime is exerted within the generally compressional European stress field, a situation unique within the Alpine system of Europe. A temporal and spatial and compositional definition of the igneous activity is of fundamental importance in order to solve the relative contributions of asthenosphere and lithosophere to the magmatic products emplaced during the Alpine orogenesis.
- Nature of geophysical anomalies. A first-order, unexplained magnetotelluric (M-T) anomaly is known north of the Tatra Mountains running parallel to the Carpathian orogenic axis (Jankowski 1967). Two competing hypotheses exist: the origin of M-T anomaly in the Carpathians has been related to the presence either of graphite or of low-resistivity brines at depth (Jankowski et al. 1985). The origin of an associated negative gravity anomaly, the axis of which is oblique with respect to the PKB, is also unclear. If the M-T anomaly is caused by low-resistivity brines, then drilling is instrumental for discovery of new renewable energy resources.
- Geodynamic reconstruction of the Mesozoic-Cenozoic basins. Particularly important are time and tectonic context of the Carpathian basins

development, followed by palinspastic restoration and paleogeographic reconstructions showing a provenance of these basins with respect to other crustal blocks, currently incorporated into the European Alpine fold belt. A better correlation of the main structural units of West and East Carpathians is one of the main goals. Verification requires the occurrence and age of the supposed oceanic floor in these basins.

- Oil generation and migration. Identification of petroleum systems of the West Carpathians and their basement and formulation of a general model for the other oil and gas reservoirs in thrustbelt setting is scheduled. To achieve project goals, scientific drilling is important.
- Regional heat-flow evolution. The Carpathians are affected by the European hotspot field, as marked by Neogene volcanism and high heat flow. The heat flow peak is now located in the Pannonian basin (Cermak 1989), To the north, Neogene volcanic rocks of the Transcarpathian Ukraine are on the Alcapa plate, while the PKB andesites and the Silesian basalts are located entirely within the European plate, and cut obliquely the Outer Carpathian nappes. This distribution may point to the ancient position of the centre of the heat-flow anomaly: the shift towards the Pannonian basin could be due to the northerly drift of the European plate, overriding a thermal anomaly.
- Identification and definition of the Cadomian-Hercynian basement structure of the Carpathians. Paleogeographic reconstructions of the basement terranes, reconstruction of the Hercynides during the circum-Carpathian geodynamic evolution and mutual relations of the fore-Alpine terranes could be addressed in detail by scientific drilling (Golonka et al. 2000).
- Paleostress evolution and its changes in horizontal and vertical section. Reconstruction of paleostress fields associated with the Carpathian development, geodynamic and palinspastic reconstruction of the Western Carpathians and Pieniny Klippen Belt during the Miocene.

Based on the current stage of knowledge, if the basement of the Alpine orogen reached and rocks responsible for M-T anomaly are to be reached, target depth for the drilling should be 8000 m. The drilling location would be optimally situated along the CELEBRATION 2000 deep seismic profile line, and profiting from already available from drillholes completed by the Polish Geological Institute and the Polish Oil Industry (e.g., Cieszkowski 1985).

3.2 Deep Subduction and Exhumation of the Lithosphere

During subduction and especially during later exhumation, tectonic accretion occurs in the subduction channel. The processes of tectonic accretion take place under varying physico-chemical and thermo-mechanical conditions (Borghi et al.1996). Metamorphic and deformational processes change the densities and mechanical behaviour of the rocks moving in the subduction channel (TAC; Engi et al.2001; 2004). The direction of particle movement in the subduction channel is controlled by the rheology and density of the rocks as well as by the 3-D distribution of heat flow through time (Platt 1993; Jamieson et al. 1998; Brouwer 2000; van de Zedde and Wortel 2001; Brouwer et al. 2004). Initial exhumation of deeply subducted material might be related to buoyant rise or forced return flow of subducted material (Chemenda et al. 2000; Burov et al. 2001; Gerya et al. 2002). Further exhumation is caused by coupled tectonic transport and erosion (Willett et al. 1993). Even late-stage exhumation into the upper crust and to the surface may strongly influence the tectonized accretionary rock assemblage. In the past few years processes in subduction channels have been successfully simulated by numerical computer models (Chemenda et al. 2000; Burov et al. 2001; Gerya et al. 2002; Roselle et al. 2002; Brouwer et al. 2004). Information related to the varying processes is stored in the mineral phases, their element composition and in nano- to micrometer scale deformational features. Because of the speed of subduction and exhumation, the mineral phases do in many cases not reach equilibrium with the surrounding physicochemical and thermo-mechanical conditions. Currently, special emphasis is given to mineral inclusions on the sub-micron scale that are formed during subduction and/or accretion and therefore give hints to the processes involved. A better understanding of elemental distribution between mineral phases and of element cycles in this special environment is needed to reveal the history of the rock transformation within the subduction and accretion channel, as well as during exhumation (Goffé et al. 2003; Zack et al. 2003; Paquin et al. 2004; Kelley et al. 2005). Various geospeedometry techniques and thermochronological dating techniques have been further developed to quantify the speed of exhumation of HP and UHP rocks. In addition, the influences of pressure on the thermochronological systems and the effects of radioactive decay (e.g., fissioning, movement of alpha-recoil nucleus) on the stability of metamorphic phases have been partly studied.

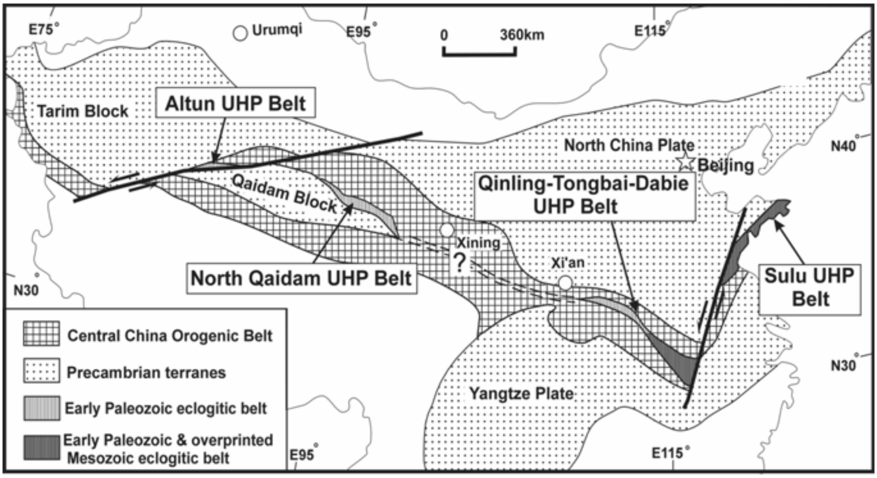

Fig. 7. Two ultra-high-pressure (UHP) events of Early Paleozoic and Triassic age are recognized in the 4000- km-long Central China UHP belt (after Yang et al. 2005). The North Dabie Shan is a good candidate for future drilling to investigate the relationship between the two events and to understand the dynamics of continental collision.

In the following, the most important tectonic scenarios for deep subduction and exhumation of lithosphere will be discussed.

Continental Lithosphere. Most ultra-high pressure metamorphic (UHPM) rocks are formed in continental plate collision zones, and have been recognized in the Caledonian, Variscan, Alpine and Himalayan orogenic belts. The oldest UHPM rocks are known from Late Precambrian and Neoproterozoic Pan-African nappes of Northern Mali and SE Brazil, where they formed in a continental plate collision zone at around 630–640 Ma. Older UHPM rocks have yet to be recognized. Because much older oceanic crust has been reported from several locations in the world, older UHPM rocks may have been formed, but not preserved. The Dabie-Sulu Triassic UHPM belt (Fig. 7) is the largest and best known occurrence in the world. It extends across central China for over 1000 km, and is offset by the Tanlu strike slip fault for about 500 km. Deep continental drilling in China (Chinese Continental Scientific Drilling Project – CCSD; Fig. 1) has sampled a 5-km-deep section of the Sulu UHPM terrane. Recent work has identified an older, parallel belt on the north side of the Dabie-Qinling Mountains, which has been dated as Ordovician (~500-440 Ma) (Yang et al. 2001 2003). This older belt extends northwestward for nearly 4000 km through the Qilian Mountains into northern Tibet where it is offset by the left-lateral Altyn Tagh Fault (Yang et al. 2005). The critical question here is the relationship between these two belts, their spatial distribution, and tectonic implications. This is a potential site for future drilling, to further investigate continental subduction and exhumation. Coesite-bearing UHP eclogite recently discovered in the Himalyan region provides a new perspective on UHPM in a collision zone and on the formation of the Tibet Plateau. This is another potential site for future drilling.

Oceanic Lithosphere. Two types of subduction, i.e., A-type and B-type, have been proposed. The A-type represents continental subduction along with UHP metamorphism, whereas the B-type represents oceanic subduction with HP metamorphism (Maruyama et al. 1996). Most known UHPM rocks occur within continental crustal sequences, and various lines of evidence indicate that large volumes of continental material have been subducted in “A-type” continent–continent plate collision zones. However, at least three UHPM occurrences, the Zermatt–Saas Zone of the Western Alps, Sulawesi in Indonesia, and the SW Tianshan in China (Fig. 1), are interpreted to have formed in deeply subducted oceanic crustal sequences, i.e., in “B-type” subduction zones. Exhumation of deeply subducted oceanic crust is even more difficult to understand than exhumation of continental crust. However, oceanic UHP rocks do occur at the Earth’s surface. Exhumation of such UHPM rocks to the Earth’s surface is likely to be a rare event requiring unusual, as yet unclear, geodynamic circumstances (Carswell and Compagnoni 2003).

Two vastly different architectures of accretionary wedges can be envisaged (see Fig. 8): closed wedge architecture and open wedge architecture. Which type of architecture is formed is mainly controlled by rates of convergence and/or subduction, the dip of the subducting plate, and the sedimentary and tectonic processes in the frontal part of the overriding plate:

Closed Wedge Architecture. At high convergence rates oceanic crust and sediments, as well as portions of the wedge sediments, enter the subduction channel and are emplaced in tectonic accretionary zones. During exhumation, their HP to UHP mineralogy is thermally and tectonically overprinted under metamorphic conditions ranging from amphibolite to lower greenschist facies. Metamorphic wedge sediments occur mainly in tectonic mélanges and imbricate “Schuppen Zones”. Their mineralogy either reflects escape from subduction (low-temperature and low-pressure metamorphic parageneses) or overprinting of blueschist facies mineralogy by greenschist to lower amphibolite facies. Remnants of former UHP and HP mineral parageneses occur in restricted areas, but in general are scarce. The pressure-temperature-time (p-T-t) paths recorded in such rocks typically suggest a clockwise evolution with thermal decompression. The Dabie Shan - Sulu UHP-HP belt is regarded as a key location to study processes within “closed wedge architecture”. Therefore, the drill core of the CCSD-ICDP drill hole at Donghai is crucial for further detailed research on the processes of subduction, accretion and exhumation in this type of setting.

Open Wedge Architecture. This scenario, related to slow convergence rates, produces different metamorphic assemblages. The accreted sediments, mostly low-grade high-p/low-T rocks in more or less coherent stratigraphic sections, do not enter the subduction channel. This rock assemblage will be overprinted under variable metamorphic conditions ranging from amphibolite to granulite facies. Where fluids are present, partial melting of large rock volumes (migmatisation) will occur. In an open-wedge setting, the sediment pile is dominated by pelitic and carbonaceous material whereas mafic rocks are less common. High-p, low-T metamorphic histories in rocks belonging to open-wedge scenarios, are recorded by carpholite or other Al-rich minerals such as chloritoid, pyrophyllite or cookeite in metapelites (Goffé and Chopin 1986; Goffé et al. 1988; Oberhänsli et al. 1995). Until recently, these associations had only been identified in Peri-Tethyan belts, and reflect the coolest prograde and retrograde P-T-t paths inferred from metamorphic belts (Becker 1993; Gebauer 1996). Petrologic data suggest pseudo-geotherms of 6 to 10°C/km (Goffé and Bousquet 1997). The stratigraphic setting, and in some cases the excellent preservation of primary stratigraphic relations (e.g., Bousquet et al. 2002), suggest that such rock sequences never entered a subduction channel, and were tectonically accreted.

The physical conditions under which HP rocks are generated coincide with the top of the seismogenic zone (Hyndman et al. 1997). Underplating of sediments and preservation of large stratigraphically coherent blocks is possible. Where sediments enter the subduction channel, conditions corresponding to either the upper or the lower sections of the seismogenic zone are recorded in the exhumed rocks. The exhumed material forms disrupted melanges or tectonically accreted sequences. Only subducted continental material seems to retain a certain lithostratigraphic coherence, as reported from UHP terrains such as the Dabie Shan – Sulu belt (e.g., Schmid et al. 2000; Xu et al. 2000; Liu et al. 2004; Xu et al. 2004) and the Himalayas (e.g., O’Brien 2001).

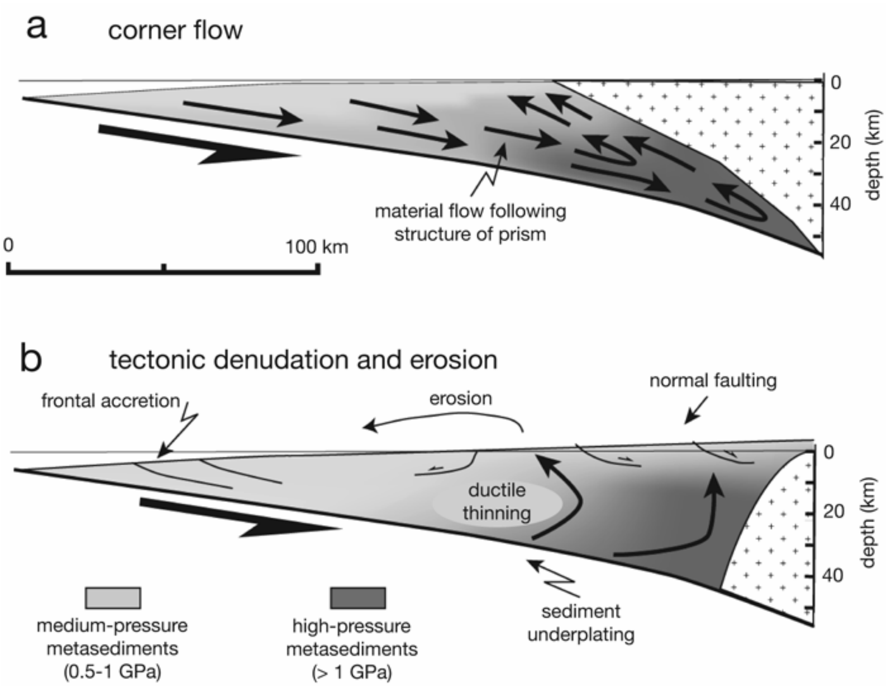

Fig. 8. Architecture of accretionary wedges and material flow as proposed by **a.** Cloos (1982, 1985), **b.** Platt (1986) or Feehan and Brandon (1999). Redrawn from Bousquet (1989)

"Open wedge architecture" has not been studied by scientific drilling, but would be important for further understanding of the processes producing the two different end-member architectures of orogens. Two key areas can be identified in which to study slowly converging accretionary systems. One is the frontal part of the Hellenic Collision Factory (see above) with strong extension and very rapid exhumation (e.g., Wortel and Spakman 1992; 2000). A second key candidate area is Makran in Pakistan and Afghanistan (Fig. 1), where there is a transect from an active accretionary complex on land to oceanic crust. Again, a joint ICDP-IODP land-sea venture should be envisaged here.

Besides geological considerations, all tectonics settings of deep subduction and exhumation of the lithosphere discussed above provide the ideal testing ground for the development new thermochronological dating techniques. To achieve progress here, it is only continuous coring by drilling that yields sufficient exposure and structural continuity.

3.3 Anatomy and Evolution of Fossil Orogens and Terrane Collages

By studying fossil orogens of different ages, with exposure of different crustal levels, orogenic process and their changes with time may be better understood. Processes that may have changed with time include how the crust has grown and stabilized, the response of the mantle to orogeny, and the production of granitoids associated with orogeny. Many ancient orogens are hidden by younger sedimentary rocks; consequently drilling is the only available means to answer fundamental questions about their age and evolution.

Aside from studying orogenic processes, scientific drilling of fossil orogens allows various geoscientific questions about the continental crust to be addressed. Boreholes (2-4 km) into stable old crust provide opportunities for heat flow measurements at depths that are unaffected by recent glaciations. Glaciation is known to significantly disturb present-day heat flow data (Kukkonen and Joeleht 2003). Long-term climate change can be studied by inversion of geothermal borehole data. Early deep biosphere and its role in fluid and gas chemistry of the continental crust is a key question calling for deep boreholes. Forms of early life can be investigated when drilling into Precambrian low-grade meta-sedimentary rocks. Economic aspects include the study of processes related to the formation of mineral deposits and low enthalpy geothermal energy. Finally, these boreholes can act as monitoring stations for longer term surface geophysical measurements (magnetotellurics, seismic, magnetics, gravity, heat flow).

Criteria for site selection include the need for drilling (limited exposure, etc.), the quantity and quality of existing seismic data, longer term monitoring aspects, and the scientific questions only a deep borehole can answer. Other surface (non-seismic) geophysics and geological models will also be important considerations in the selection of any potential drilling site. Reflection seismic data acquired over active orogens often result in poor images of the crust. For example, the modern Banda arc (Snyder et al. 1996) is generally transparent, if compared to the Paleozoic arcs of the Urals (Steer et al. 1998) or the Svecofennian orogen of the Baltic Shield (BABEL Working Group 1993). Is this inherent to modern crust, or is it due to poorer signal quality in modern orogens, caused by large volumes of low velocity material overlying the more competent deeper crust? Are the crustal structures observed in fossil orogens on reflection seismic sections really present in modern orogens, and just unobservable with seismics, or is this difference due to unfinished metamorphic processes or removal of fluids from the rocks? These are very fundamental questions that cannot be ultimately answered without comparative drilling in young (see sections 3.1 and 3.2) and old (this section) orogens.

Crustal stacking, heating and exhumation are important components of collisional orogeny (see above). During convergence the crust is shortened, thickened, and deformed. The re-distribution of radioactive heat sources by crustal thickening, partial melting and melt transport to the upper crust define metamorphic P-T-t paths and result in thermal stabilization of the lithosphere. Thickened crust may become gravitationally unstable, leading to syn- or post-orogenic extension (Dewey 1988). This process is closely related to the exhumation of high pressure and ultra-high pressure fragments, and even mantle slices. How these slices are brought to the surface is an important question that can be addressed by drilling in old orogens that possess a geometry caused by complete collapse (e.g., the Norwegian Caledonides). Also, recent seismic reflection data from FIRE (Finnish Reflection Experiment) over the Paleoproterozoic Svecofennian orogen (1.89-1.87 Ga) show clear listric reflectors extending from the surface to the lower crust. These structures may represent a cycle of crustal shortening, stacking and late extension during this orogeny. Understanding the nature of these hidden reflectors is crucial to documenting syn- or post-orogenic extension.

In the Paleozoic Scandinavian Caledonides (Fig. 1), nappes have been transported hundreds of kilometers from west to east. How has the crust below the basal thrust deformed? Reflection seismic data over the Caledonides show clear deformation patterns (Juhojuntti et al. 2001). Drilling 2-4 km into the crust will answer questions about the rheological state of the crust during deformation, later (Cenozoic) uplift processes, the nature of present-day and ancient fluids in the decollement zones, as well as provide important constraints on reflection seismic and other geophysical data.

Pre-existing structural discontinuities in the lithosphere often define sites of later deformation; consequently it is important to understand the structures of ancient orogens and the role they play in the evolution of the crust. For example, Mesozoic strata of the Crimean Mountains in the southern Crimean Peninsula (Fig. 1) have been deformed during the Jurassic-earliest Cretaceous (poorly defined) and post-middle Eocene (well-defined) via transpression (Stephenson et al. 2004). Geophysical methods (seismic reflection, magnetotellurics) aid in mapping these structural discontinuities at depth, for example the geomagnetic anomaly along the Pieniny Suture Zone (see section 3.1.5) stretches several hundreds of km (Jankowski et al. 1985).

Recent deep drilling Outokumpu, eastern Finland (Fig. 1), has shed new light on the deep structure of a classical Precambrian ore province containing massive sulphide deposits in an ophiolitic and metasedimentary setting. Strong seismic reflectors (Fig. 9) are being re-interpreted and new ideas on crustal evolution based on recovery of saline fluids and gases have emerged. Paleoproterozoic thrust sheets may be much thicker than anticipated. Fundamental questions regarding the deep biosphere, origin and motion of deep fluids, the stress field, seismic structure and the Phanerozoic thermal history of the eastern part of the Baltic Shield (Kukkonen 2004) may be addressed and answered here.

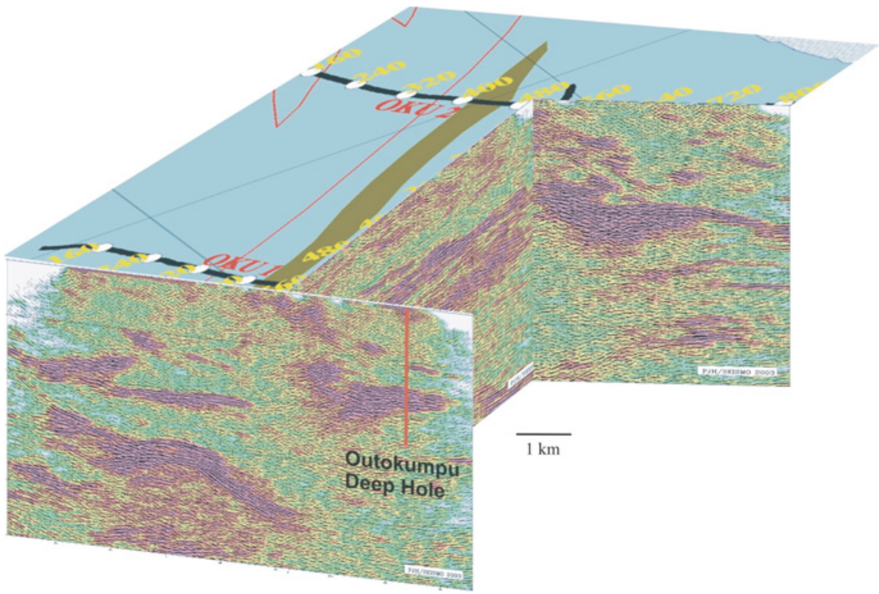

Fig. 9. Deep drilling (2.5 km) into a Paleoproterozoic ophiolitic and metasedimentary formation in Outokumpu, eastern Finland, has revealed the nature of strong reflectors in the upper crust. These consist of alternating layers of serpentinite, skarn rocks and black schists enveloped by mica schists. The 3-dimensional model was constructed from migrated high resolution reflection seismic data by the FIRE project (Kukkonen et al. 2004) and a lithological surface map (Geological Survey of Finland). The seismic sections extend to a depth of 5 km. The amplitude scale of the reflectors has been color coded for clarity indicating higher reflection amplitudes. Colors of the surface geological map: blue - mica schist; brown - serpentinite, skarn rock, and black schist.

Apart from answering overriding questions in tectonics and Earth history and integration with other research themes, future fossil orogen research boreholes at all other conceivable locations will need to be geared at:

- Saline fluids and gas sampling,
- Deep biosphere studies,

- Heat flow measurements,
- Oriented core recovery,
- Petrophysical property measurements,
- Fission track studies.

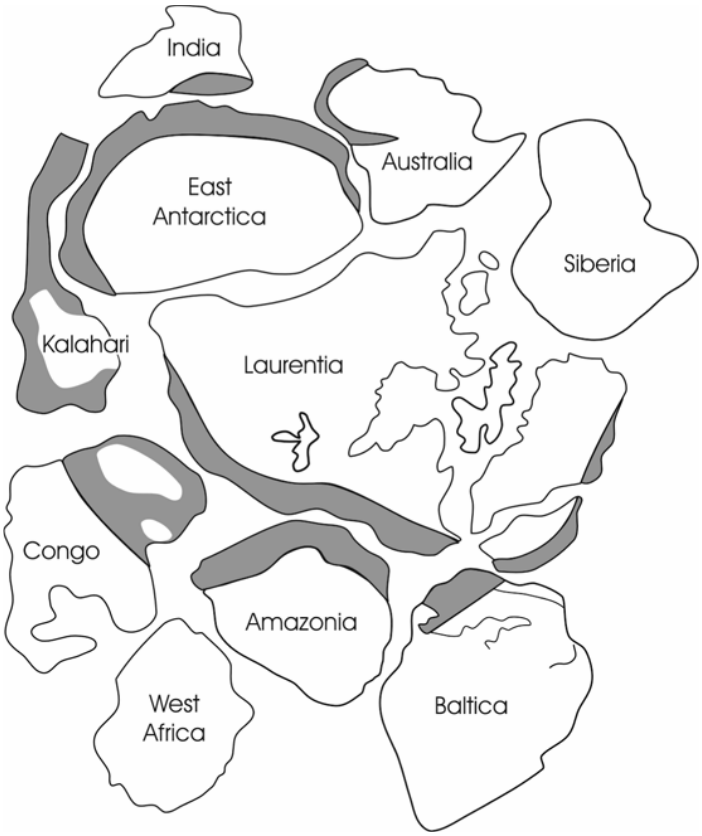

Fig. 10. Tectonic reconstruction of Rodinia (after Hoffman 1991), based on linking Grenville-age orogens (grey) found around the world. Ancient collisional orogens like the Grenville are repositories of economic mineral resources on a global scale.

Drilling objectives will focus on answering questions about orogenic processes in time and space. Other ICDP themes integrate directly into all potential drilling sites, especially climatic disturbances up to 100,000 years ago, because deep boreholes in crustal rocks provide unique laboratories to study major changes in surface temperatures. Economic mineral deposits are also important as many types of mineral deposits are associated with collisional processes and therefore ancient orogens. Extensive study of old orogens by drilling will ultimately improve our understanding how are continental shields being born, how they amalgamate to form terrane collages, continents and supercontinents (Fig. 10), and how they are being fragmented and destroyed.

4 Technological Needs

4.1 Drilling Technology

Most of the scientific drilling proposed here may be accomplished using drilling rigs and equipment available on the market for hydrocarbon and ore exploration drilling today. However, any program of scientific drilling addresses questions that cannot be answered without the use of novel and dedicated technology, to be developed within the framework of the individual projects. Therefore, extensive accompanying programs of borehole logging and on-site geophysical and geochemical monitoring will require a continuous effort of building and improvement of technologies, especially those developed and used in the course of earlier ICDP-sponsored continental deep drilling ventures. Examples pertaining to convergent and collisional plate margin drilling are the German KTB wells, the Dabie-Sulu Project in China, and the recently completed SAFOD drilling on the San Andreas Fault near Parkfield, California, USA (Fig. 1). Some of the targets identified above, especially those involving penetration of plate boundary zones and the associated seismogenic zones, may require drilling to unprecedented depths, and present major technological challenges.

4.2 Requirements for Instrumentation of Drill Holes

Instruments needed for convergent-boundary borehole observatories fall into two categories, the “standard” instruments that in principle should be used in most observatories and the special-purpose instruments that are designed to monitor processes of particular importance to a given borehole site. The standard set should includes a broadband seismograph, a tilt meter, a borehole strain meter, at least one fluid pressure sensor, and a number of temperature sensors at different depths.

The variety of special-purpose instrumentation can be limited only by one’s imagination. In the following, only a few examples are given.

Hydrogeological transients in association with seismic and aseismic tectonic strain changes have been both puzzling and exciting. Well water level is known to fluctuate before, with, and after earthquakes. For many (currently 29) instrumented ODP and IODP boreholes, fluid pressure changes have been demonstrated to be sensitive, robust, and to be very broadband strain indicators. In more advanced recent designs, fluid pressures are monitored in isolated depth sections communicating with rock formations of different hydraulic and mechanical properties (Davis and Becker 2004). These sensors record regular (such as tidal) pressure variations as well as tectonic pressure pulses.

Temperature variations are sensitive indicators of fluid flow. Temperatures can be monitored at carefully chosen discrete depths using resistor thermal sensors or for a continuous depth range using the fiber-optic *Distributed Temperature Sensing* (DTS) instrument (Förster et al. 1997; Macfarlane 2002). Successful applications of the latter have been made within ICDP in the Hawaii project (Büttner and Huenges 2002) and in the Mallik gas-hydrate project in Canada (Henninges et al. 2005), although the currently limited life-span of fiber-optic instruments is of some concern for long-term (decades) observatories.

For strain monitoring, the use of the fiber-optic *Bragg-grating technology* (FBG) was successfully demonstrated in the Corinth Rift Laboratory (Moretti et al. 2002). This technology was combined with a downhole electrode array to study the long-term deformation and hydraulic properties of a major fault zone. While the DTS technology can be employed both inside and outside borehole casing, the FBG technology to measure strain is restricted to use outside casing. Outside-casing installations have to be made during borehole casing.

Recently, there have been approaches to use *downhole triple axis accelerometers* (TAA) as part of the casing. These devices will allow for continuous monitoring of the seismic background with very low signal strengths. The installation of monitoring instruments outside the borehole casing constituting a “smart casing” has the advantage that the inner part of the cased borehole can be used for other instrumentations or regular logging runs.

For near-field monitoring of active faults, many of the technologies currently designed and employed at the SAFOD site can be used (see Reches and Ito this volume). Fluid samplers may be needed for geochemical monitoring and analyses. The installation of the standard and special-purpose tools/techniques requires sophisticated engineering design so that they do not interfere with one another’s operation and they can function at desired pressure and temperature conditions. The design needs to begin developing at an early stage as part of the drilling plan.

5 Synopsis

Here, we have developed a comprehensive initiative to drill the continental crust bordering modern and ancient convergent and collisional plate boundaries, encompassing the following:

1. Dynamics of active subduction and collision zones, with focus on the seismogenic zone at the plate interface, and the distribution of deformation and seismicity,
2. The role of mantle plumes in orogeny,
3. Supra-subduction magmatism in arc systems,
4. The geological manifestation of deep subduction and exhumation of the lithosphere, and
5. Aspects relating to continental birth and growth through Earth history.

ICDP drilling in convergent and collisional plate margins faces unprecedented challenges regarding drilling technology, drilling depth and requirements for long-term monitoring of Earth processes in downhole observatories.

The continental areas bordering convergent and collisional plate boundaries host the vast majority of modern megacities and industrial installations on Planet Earth, and at the same time are loci of major earthquakes, tsunamis, volcanic eruptions and other associated great natural threats to human life and to economies. As 60% of Earth's population lives within the frontal 50 km of the coast in or near convergent or collisional plate boundaries, there is a strong need for scientific and economic efforts, to elucidate and understand the processes responsible for such geohazards as well as for strategies aiding their mitigation. Scientific drilling will play a vital role in such studies and is an integral part of this effort.

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Natural Resources

Wilfred A. Elders[1] and Scott R. Dallimore[2]

[1]Department of Earth Sciences, University of California,
Riverside, California 92521, USA
e-mail: elders@ucr.edu (corresponding author)

[2]Geological Survey of Canada,
Sidney, British Columbia V8L 5S, Canada

Abstract

The vast scale of drilling worldwide for economic goals dwarfs the number of scientific drilling projects. This alone creates a strong incentive for the ICDP to collaborate with industry. Given the current world energy situation, the growing amount of drilling for unconventional energy resources is increasing opportunities for such collaboration. Two examples are discussed here, the Mallik Gas Hydrate Production Research Program, and the ongoing Iceland Deep Drilling Project. The Mallik project was collaboration between industry and government agencies that investigated gas hydrates in permafrost in Arctic Canada. Gas hydrates are a new, and potentially large, source of energy. Past periods of rapid atmospheric warming in the geologic record may have been initiated, or significantly accelerated, by dissociation of such gas hydrates. The Iceland Deep Drilling Project is another collaboration between industry and government, but it is investigating unconventional geothermal resources in Iceland. This project will drill a series of 4 to 5 km deep wells in the search for supercritical hydrothermal fluids at temperatures of 450-500 ^{o}C. It is estimated that power output from wells producing supercritical fluid will be an order of magnitude greater than produced from conventional geothermal wells. Supercritical fluids play a fundamental role in coupling magmatic and hydrothermal systems on mid-ocean ridges. In the future, many other important scientific questions could be addressed by the ICDP participating in similar natural resource drilling projects.

1 Introduction

Of all the themes discussed at the conference “Scientific Drilling 2005, a Decade of Progress and Challenges for the Future”, held in Potsdam, Germany, from March 29 to April 1, 2005, none is more important to society than the topic of *“Natural Resources”*. According to the data of the Population Division of the United Nations, during the two and a half days of the ICDP conference, the world’s population of 6.46 billion grew by more than 506,000 humans (www.un.org/esa/population/unpop.htm). It is expected to rise by 1.5 billion in the next 15 years, with most population growth occurring in the emerging economies of China and India. The increase of 2.66 billion people expected by 2050 exceeds the world population that existed in 1950. Accompanying this growth is a relentless demand for natural resources to sustain economic development and to support rising standards of living. A key priority for the global community, now, and in the future, is to identify and develop increasingly scarce natural resources, while at the same time protecting the environment.

There can be no doubt of the importance of natural resources to society, but it is interesting to note that the comprehensive document that led to the founding of the International Continental Scientific Drilling Program (Zoback and Emmerman 1993) did not include “Natural Resources” among its scientific themes. However drilling carried out for oil, natural gas, coal, metallic and non-metallic ores, and groundwater, etc., is the basis of virtually every natural resource industry. Many of the basic science themes discussed, both in the 1993 report and in this document, have significant linkages to natural resources, and vice versa. For example, our current knowledge of the age, nature, and distribution of metallic deposits in the Sudbury Impact Structure in Canada has been gained from the extensive drilling and mining there for metallic ores. It is clear that a very broad range of fundamental scientific questions can be addressed while drilling for natural resources, but establishing an appropriate balance between purely scientific and applied natural resource components of a scientific drilling project is a challenge that must be addressed.

The panel on Natural Resources convened at the 2005 conference began its deliberations by asking *if* the ICDP should establish a unique role in the area of natural resources and, if it does, *what* should that role be? The consensus of the panel was that, because of the ever-growing *societal relevance* of environmentally sustainable natural resources, the ICDP should recognize this topic as a unique theme and should try to define future priorities for scientific drilling within that broad scope. Funds available to the ICDP for drilling are, of course, very limited compared to the enormous drilling budget available to the worldwide natural resource industry. The panel therefore affirmed the principle that ICDP's limited funds should not be used in ways that subsidize, or compete with drilling that is more properly the domain of industrial and government entities concerned with the development of natural resources. When an ICDP funded drilling project involves a research theme related to natural resources, it should strive to focus on scientific questions of broad global significance and not on narrow economic issues such as exploration for, or assessment of, natural resources. The ICDP must be flexible in promoting and advancing specific drilling activities that concern leading-edge research on natural resources. The analogy made was that ICDP should be a "lighthouse", rather than a leader, in this field. Just as lighthouses guide ships to safe destinations or warn of dangers, the ICDP should be a catalyst to encourage novel drilling-related research on natural resources. Where possible ICDP should attempt to address broad over-arching research questions that are not routinely addressed by industry and the ICDP should rank highly research proposals that have a potential for positive contributions to resource and environmental problems.

One way in which the ICDP could act as such a catalyst is to encourage collaborations with natural resource developers that are mutually beneficial both to the natural resource industry and to the international scientific community. Ideally such a mutually beneficial project would be one in which an industrial partner plans to drill a target of potential economic interest that also provides the opportunity for the scientific partners to address important scientific questions of global significance. Both the industrial and the scientific partners could then contribute funds, technical expertise, facilities and equipment to the project and make available borehole samples and data, in a spirit of mutual collaboration. The fact that such collaborations have hitherto been infrequent is due to the special circumstances that must exist to make such collaborations feasible. Questions such as the status and ownership of proprietary data, cost sharing, liability, and integration of the timetable and goals of the industrial and scientific partners have to be addressed. None-the-less, the panel believes that there is a great and untapped potential for such collaborations *if* these issues can be successfully addressed and overcome.

1.1 Some Background History on Drilling for Natural Resources and for Scientific Goals

Although the following historical digression discusses two examples of major drilling projects that predate the formation of the ICDP, these projects are relevant to this chapter because it illustrates how positive synergies can be built between research drilling for purely scientific purposes and drilling aimed at understanding, exploring for, and assessing natural resources. In both cases, a resource oriented drilling program morphed into a scientific drilling program (Elders 1989). The first example of this evolution was the world's deepest scientific drilling program, the 12 km deep borehole SG-3, drilled 250 km north of the Arctic Circle in the Kola Peninsula of Russia (Kozlovsky 1986). When this borehole began, in May of 1970, the aim was to investigate the downward continuation of the supracrustal Proterozoic strata of the nickeliferous Pechenga complex of the Zapoljarniy mining district, and to seek information on the deeper extent of the ore bodies. At 6.8 km depth the borehole entered Archean plagiogneisses and amphibolites. It was decided to continue and, at that point, the drilling target became the penetration of several flat-lying seismic reflectors in the Archean basement. Thus, from being a drilling project initially concerned with ore mineralization, the project became one dedicated to the investigation of the Archean rocks and documentation of a reference section that could be used to calibrate deep seismic profiles, data that could have wide application in the study of the Earth's continental crust. By July 1984 the borehole had penetrated to a depth of 12,063 m (Kozlovsky 1986).

The second example is a deep drilling project that started out to explore for natural resources and that by default became a purely scientific project. This was carried out in the Siljan Ring, a 52 km diameter, 360 Ma old, impact structure developed in Precambrian granites, 250 km north of Stockholm, Sweden (Bodén and Erikson 1988). The charismatic astronomer Thomas Gold (perhaps best known for explaining that pulsars are rotating neutron stars) instigated this project. He championed the hypothesis that methane and other hydrocarbons originate from the mantle as remnants of the abiogenic, primordial material that accreted to form planet Earth. Furthermore, he asserted that brecciation induced by impacts of large extraterrestrial bolides should create ideal conduits to tap this resource (Gold 1999). His persuasive arguments led the Swedish State Power Board to drill a 6.8 km deep borehole in 1986-87 to penetrate seismic reflectors that Gold believed were impermeable cap rocks formed by hydrothermal activity induced by the bolide impact. However the three high-amplitude seismic reflectors that were drilled proved to be diabase sills that predated the impact event by 500 Ma. The background levels of hydrocarbons encountered in the granitic rocks were several orders of magnitude lower than those expected in a hydrocarbon reservoir. Although the contribution of the Siljan borehole to natural resources was negative, it provided scientific data on impact structures, and on the nature of fluids and seismic reflectors in crystalline rocks. Given the high cost of this deep borehole, it was extremely unlikely that it would have been drilled in Sweden purely for research purposes.

1.2 Scientific Drilling and Energy Resources

Given the enormous diversity of the research on natural resources, the panel decided to focus on the theme that they regarded as having the highest societal relevance, the role of scientific drilling in the context of the *energy resources*. The need to supply clean, environmentally friendly energy is a top priority today and this need will grow in importance in the future. As pointed out by Fridleifsson (2005), "some 70% of the world's population lives at a *per capita* energy consumption level that is one-quarter of that of Western Europe, and one sixth of that of the USA. Two billion people, a third of the world's population, have no access to modern energy services".

Table 1 shows the worldwide total primary energy consumption in 2001 was 418 EJ/a, of which fossil fuels represent 80% of the total (WEA 2004; cited in Fridleifsson 2005). Oil remains the most important of these sources of energy, representing about a third of this total, followed by coal and natural gas, each representing slightly more than a fifth of the total. Together "renewables", dominated by hydroelectric power, provide about 14% of the total, with the "newer" renewable such as geothermal, solar and wind, etc., comprising only 2.2%.

An inkling of future trends in energy can be gained from the observation that in August 1993, at the time of the first conference on continental scientific drilling in Potsdam in 1993, the price of a barrel (bbl) of crude oil averaged 14 USD, whereas in April 2005, at the time of the second ICDP conference, that price had risen to 58 USD and subsequently it has exceeded 70 USD (6.96 bbl = 1 metric ton of 25^{o} API crude oil).

In addition to increasing costs, a major concern about the increasing reliance on petroleum fuels is their high rate of depletion. More than 50 years ago, M. King Hubbert made the first serious attempt to predict the decline of petroleum reserves by modeling their extent, their rate of production, and their rate of discovery, and hence to estimate their rate of depletion. In 1949 these studies led him to make the startling prediction that the fossil fuel era was coming to an end (Hubbert 1949; see also htpp://www.hubbertpeak.com/). In 1956 he predicted that U.S. oil production would peak about 1970 and decline thereafter. Although his analysis was met with skepticism at the time, it proved to be remarkably accurate. U.S. oil production peaked at about nine million bbl/day (MMbd) in 1970 and has subsequently declined to about six MMbd today (Deffeyes 2001). Subsequently Hubbert extended his analysis to world oil reserves and to estimates of when world oil production would begin to decline. This analysis has been criticized, updated, and refined by numerous authors (van der Veen 2006). Various refined estimates of the year when world oil production will peak, and then decline, compiled by Hirsch et al. (2005), range from 2005 to 2025.

Table 1. World Energy Consumption in 2001 (WEA 2004)

Energy Source	**Primary Energy**	
	EJ	% of Total
Fossil Fuels	**332**	**79.4**
Oil	147	35.1
Natural Gas	91	21.7
Coal	94	22.6
Renewables	**57**	**13.7**
Large Hydro >10 MWe	9	2.3
Traditional Biomass	39	9.3
"Newer" Renewables	9	2.2
Nuclear	**29**	**6.9**
TOTAL	**418**	**100**

MWe = a Megawatt of electric power, EJ = an Exajoule, a quintillion (10^{18}) Joules, Newer Renewables = geothermal, solar, wind, tidal and small hydro

According to Annual Energy Outlook for 2005 of the Energy Information Administration of the US Department of Energy (accessible at http://www.eis.doe.gov/), it took the world 125 years to consume the first trillion barrels of oil, but the next trillion barrels will be consumed in the next 35 years. In 2005 the world demand for oil is approximately 82 MMbd, but this is expected to grow to 121 MMbd by 2030. Two-thirds of this increase will take place in developing countries, especially China and India. Fuel demand in China grew by 15% in 2004 alone and China overtook Japan to become the world's second largest user of oil (Annual Energy Outlook 2005). Important environmental issues complicate this prognosis for world supplies of fossil fuels. According to Musser (2005, p. 44) the rate at which we produce carbon dioxide, the main greenhouse gas, is already three times as fast as the ocean and land can absorb it. In response to this trend the world's developed countries (minus USA and Australia) agreed on the Kyoto Protocol on Global Warming in 1997 and this treaty was implemented in February 2005. It calls for a drastic reduction in the emission of greenhouse gases worldwide by 2012 to 5% below the levels produced in 1990. It also called for an international cap-and-trade system or “carbon market” to limit carbon dioxide emissions produced by the burning of hydrocarbon fuels by industry The European Union launched such an emissions trading scheme on January 1st 2005.

The panel on Natural Resources concluded that these environmental issues make it imperative that the ICDP should seek opportunities for scientific drilling concerned with energy research, specifically projects concerned with the science of “unconventional” or “alternative” energy resources that are less polluting than conventional fossil fuels. Since its formation the ICDP has been involved in only two scientific drilling projects that involve energy research. These are the Mallik 2002 Gas Hydrate Production Research Well Program that dealt with gas hydrates, and the on-going Iceland Deep Drilling Project, an investigation of unconventional, very-high temperature, geothermal resources. Both of these projects involve fruitful collaborations of the ICDP with industry and government agencies.

2 Gas Hydrates

Gas hydrates are ice-like solids consisting of a lattice of hydrogen-bonded water molecules forming cage-like structures, each of which can contain a single molecule of natural gas. Methane hydrate, thought to be the most widespread in nature, is stable within geologic settings where there are relatively high pressures and cold formation temperatures (Fig. 1). Geophysical and drilling studies have identified gas hydrates around the world in marine settings where water depths are greater than 500 m (Kvenvolden and Lorenson 2001). Very concentrated deposits have also been found in terrestrial settings in the Arctic in association with thick permafrost (Collett and Dallimore 2000). Because of their unique molecular structure, one unit volume of gas hydrate can contain 160 times, or more, of natural gas compared to free gas at atmospheric conditions. Global estimates of the abundance of gas hydrate vary widely (Kvenvolden and Lorenson 2001; Milkov 2004), but they all indicate that the volume of natural gas stored within marine and terrestrial gas hydrate deposits is enormous. Indeed there is thought to be more carbon stored in the geosphere as gas hydrate than all conventional and unconventional hydrocarbon sources combined.

ICDP’s mandate to undertake continental scientific drilling makes permafrost-associated gas hydrates on land of particular interest. Because cold climate conditions have prevailed in the Arctic since Pliocene times (about the last 1.88 Ma), permafrost may be up to nearly a kilometer thick in some areas. Permafrost, defined formally on a thermal basis as sediments that are below 0°C for two calendar years, or longer, creates unique geothermal conditions and in some instances unique formation pressures. Maps of present day permafrost distribution reveal that about 20 percent of the land area of the northern hemisphere is underlain by permafrost (Fig. 1). Subaerial emergence of the Arctic continental shelf to current water depths of 120 m during repeated Pleistocene glaciations, subjected the exposed shelf to temperature conditions favorable to the formation of permafrost and gas hydrate. Thus, it is speculated that "relic" permafrost and gas hydrate may exist on the continental shelf of the Arctic Ocean in present water depths as shallow as 120 m.

2.1 Gas Hydrates as an Energy Resource

International interest in gas hydrate deposits has grown in the past decade, in part due to the recognition that natural gas, as an energy commodity, is likely to increase in importance in the future within the global economy. As one of the cleanest burning fossil fuels, demand for natural gas is projected to grow in the first decades of this century, at the same time that supply from conventional sources is declining in many areas. The vast deposits of gas hydrate in the Arctic are seen as possible new sources of natural gas. However, there are many challenges to be overcome before widespread production of natural gas would be possible from gas hydrates. For instance, there is considerable uncertainty regarding the most suitable methods of production, and the environmental implications of gas hydrate production are unknown. Detailed knowledge of its distribution and abundance at a reservoir scale is limited and significant gaps in scientific knowledge exist about the mode of occurrence, physical and geophysical properties, microbiology and stability over geologic time. Because gas hydrate is only stable at *in situ* pressure and temperature conditions, it is very difficult to collect high quality core. The investigation of gas hydrates therefore requires geophysical studies, and advanced methods of scientific drilling and coring.

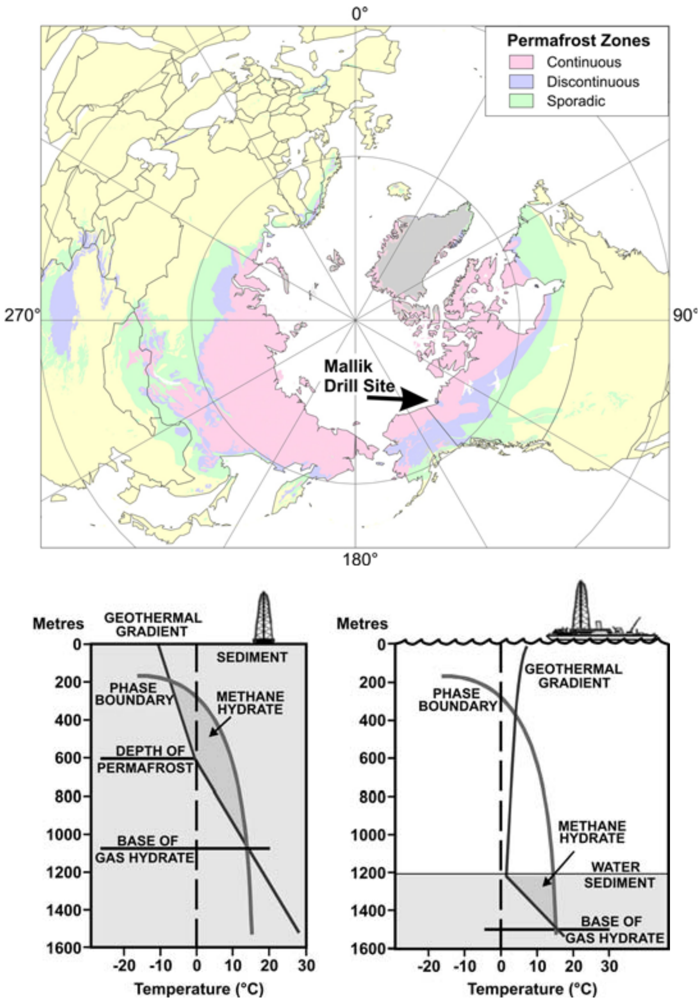

Fig. 1. Circum–Arctic map showing permafrost distribution and location of the Mallik 2002 field site (top). Pressure-temperature stability zone for methane hydrate occurring in permafrost and marine settings (bottom).

2.2 Climatic and Environmental Considerations

Perhaps more than any other naturally occurring material on earth, gas-hydrate-bearing sediment exhibits extraordinary changes when the gas hydrate it contains dissociates to gas and water. Since gas hydrate typically acts as cement within the sedimentary matrix, its dissociation may cause consolidation of the sediments and a resulting reduction in their strength. Release of gas during dissociation may also dramatically affect the geo-pressure regime; the released gas may move to shallower depths or even discharge to the surface. Because methane, a greenhouse gas twenty times more potent than carbon dioxide, is the most common form of gas hydrate in nature, there is considerable interest in assessing the potential impact of gas hydrate on global climate change. Some workers have speculated that periods of rapid atmospheric warming in the geologic past may have been initiated or significantly accelerated by the release of methane from dissociating gas hydrate deposits (Kennett et al. 2003; Dickens 2003). However, little is known about the sensitivity of natural gas hydrate deposits to climate warming or about the flux of natural gas to the atmosphere. These gaps in knowledge represent limitations for global-climate predictive models.

Gas hydrate deposits can be also be significant geohazards. Structural foundation problems can be encountered when gas hydrates are destabilized by changes in the *in situ* pressure or temperature regimes that are induced either naturally or by human activities (e.g., Collett and Dallimore 2000). Under certain conditions, free-gas-bearing sediments can pose a significant slope-stability hazard where gas-hydrate-bonded sediments are underlain by weaker gas-hydrate-free sediments. Gas flows while drilling and other drilling problems have also been documented.

2.3 The Mallik 2002 Production Research Well Program

In 2002, ICDP enabled its first scientific drilling program in the Arctic and its first gas hydrate research study. The Mallik 2002 Gas Hydrate Production Research Well Program was complex, novel and very challenging. The fieldwork was undertaken in the middle of winter in Arctic Canada, more than 3000 km by road from most supply bases in southern Canada. Prior to the endeavor no gas hydrate core had been collected from a gas hydrate deposit on land and no constrained data set existed on the production of natural gas hydrate. The Mallik project was undertaken as a multidisciplinary endeavor related to gas hydrate production, with broad fundamental science objectives and focused engineering goals. In addition to ICDP, partners included the Geological Survey of Canada (GSC), the Japan National Oil Corporation (JNOC), the GeoForschungsZentrum Potsdam (GFZ), U.S. Geological Survey (USGS), the India Ministry of Petroleum and Natural Gas (MOPNG), the BP-Chevron-Texaco-Burlington joint venture parties, and the U.S. Department of Energy (USDOE). The operational cost of the drilling program were approximately \$17M (CDN) with ICDP contributing approximately \$2.0M based upon a proposal by principal investigators S.R. Dallimore, T.S. Collett, T. Uchida and M.

Weber. Nearly all of the ICDP funds contributed to expanded fundamental research building upon broad applied research goals related to evaluating the energy potential of gas hydrates. ICDP enabled more than 20 novel investigations of specialized gas hydrate core, down hole and surface geophysical studies, and geothermal modeling. ICDP also played a significant role in managing the data generated from the project.

Fieldwork began in December 2001 and continued to the middle of March 2002. Two 1188 m deep science observation wells and an 1166 m deep production research well, with 40 m offsets, were drilled and instrumented. The central production research well included continuous coring through the gas hydrate interval, advanced well logging and *in situ* measurements of the ground temperature regime, using fiber optics instrumentation. Full-scale field experiments in the production well monitored the gas release and the physical behavior of the hydrate deposits in response to depressurization and thermal stimulation. The observation wells facilitated cross-hole tomography and vertical seismic profiling experiments (before and after production) as well as the measurement of *in situ* formation conditions. A post-field research program included laboratory and modeling studies to document the sedimentology, physical/petrophysical properties, geophysics, geochemistry, and molecular chemistry of the Mallik gas hydrate accumulation. With such a wealth of field and laboratory data the central engineering goal of the project was achieved, i.e. verification and improvement of simulation models of gas hydrate reservoirs.

By many measures, the Mallik 2002 Production Research Well Program was a success story for ICDP and the Mallik partners. ICDP truly served as a scientific "lighthouse", playing a direct role in initiating a broad multidisciplinary research agenda. Of the 62 peer-reviewed papers in the results volume (Dallimore and Collett 2005) scientists supported by the ICDP led half. The Mallik project was truly international. In total, the results volume included 170 co-authors from Japan, Canada, Germany, USA, India and China. Because gas hydrate science is a relatively new field, many of these studies were ground breaking, contributing to a very successful integration of applied and basic science.

3 Geothermal Resources

An appealing alternative to using fossil fuels is to turn to so-called "renewable sources". Table 2 shows an estimate of the "technical potential" of these renewables, that is their yearly availability, based on data from 2001, without considering economic, environmental or political factors

(WEA 2004; cited in Fridleifsson 2005). Clearly renewable energy will play an increasing role in the world's energy picture if the economic, environmental or political factors can be addressed satisfactorily. As can be seen from the WEA data, geothermal energy, used both for generation of electricity and for direct applications such as space heating and industrial processes, is one of the most promising alternative energy resources, especially in areas of high crustal heat flow.

Unlike hydropower, biomass, solar, etc., geothermal energy is clearly a natural resource that requires drilling for its exploration, assessment, development and production and so the ICDP has the opportunity to play a "lighthouse" role in fostering research on this topic. Heat flow is a fundamental characteristic of planet Earth and continued production of heat by radioactive decay within the Earth drives many geologic processes. In the Earth's crust it is manifested as conductive heat flow, the advection of hydrothermal fluids, and the advection of magma that causes igneous intrusions and volcanic eruptions. Thus geothermal resources are among the most attractive targets for the ICDP, for both for their fundamental scientific interest in understanding the active processes that shape the planet, and for their potential beneficial impact on the societal need for energy. (See the Chapter "Volcanic Systems and Thermal Regimes" in this volume).

Table 2. The World Energy Authority's Estimate of the Technical Availability of Renewable Energy Resources (WEA 2004)

Energy Source	EJ/a
Hydropower	50
Biomass	276
Solar	1575
Wind	640
Geothermal	5000
TOTAL	7541

EJ/a = an Exajoule (10^{18} Joules) per annum

Stefansson (2005) has estimated that the heat stored in only the upper 3 km of the rocks of the continents is 12 x 10^{12} GWh (A gigawatt hour = 1 million watt hours) or 43 x 10^{6} EJ. Therefore the heat stored in the upper 3 km of the continental crust could, in principle, supply the energy needs of mankind for 100,000 years at the present rate of consumption (Stefansson 2005). However, the heat flow from the mantle is most intense at plate boundaries, where volcanoes are concentrated, rather than within tectonic plates. Accordingly, it is at plate margins where the greatest potential for utilization of geothermal energy exists. Based upon an empirical relationship between the number of active volcanoes and the technical potential of geothermal fields in eight different regions across the world, Stefansson (2005) calculated the technical potential for electrical generation of geothermal fields of the world as a whole to be about 50 GWe (a gigawatt electrical = 1 billion watts of electric power) with a corresponding potential for direct use of about 1 TWt (a terawatt thermal = 1 trillion watts of thermal power).

3.1 Geothermal Resources as Current Sources of Energy

This technical potential for geothermal energy is beginning to be developed. According to Bertani (2005), the total worldwide installed electrical generating capacity using geothermal heat in 2004 was only 8,900 MWe, but it is growing rapidly. In 2003 geothermal resources supplied 57,000 GWh of electricity, an increase of 15 percent from 2000 and 50 percent from 1995 (Bertani 2005). Karl Gawell, Executive Director of the US Geothermal Energy Association reports that, "Geothermal energy is today meeting the total electricity needs of some 60 million people worldwide - roughly the population of the United Kingdom," (http://www.geo-energy.org, accessed 17/05/05). Geothermal energy today is being produced in 24 countries and on all continents except Antarctica. In 2004 countries producing electric power from geothermal resources were: Australia, Austria, China, Costa Rica, El Salvador, Ethiopia, France (Guadeloupe), Germany, Guatemala, Iceland, Indonesia, Italy, Japan, Kenya, Mexico, New Zealand, Nicaragua, Papua New Guinea, Philippines, Portugal (Azores), Russia, Thailand, Turkey, and the United States. The United States continues to produce more geothermal electricity than any other country, comprising some 32 percent of the world total, but several countries are moving aggressively ahead with new developments, particularly the Philippines and Indonesia. Since 2000 there has been significant drilling for geothermal resources in 19 countries. More than 290 wells were drilled, averaging about 2 km deep, for a total of 560 km of drilled depth. Given current economic trends, the present pace of geothermal drilling will accelerate rapidly in the near future, which should present numerous opportunities for the ICDP to participate in drilling for research purposes.

Geothermal energy is an environmentally benign resource and this factor will become of increasing importance in contributing to its development. Although geothermal production wells usually produce fluids with salt concentrations that may be toxic to terrestrial plants, such fluids are not released to impact the environment. Two different strategies are used to deal with these brines. (1) *Flashed Steam Cycle.* If the temperature of the produced geothermal fluid is >200 ^{o}C, it is partially flashed to steam, the separated steam drives turbines and the remaining unflashed fluid is usually disposed of by injection into deep wells in such a way as to maintain pressure in the hot reservoir, or in cold climates may be used for space heating. (2) *Binary Cycle.* If the temperature of the fluid is <200 ^{o}C it is more efficient to utilize a heat exchanger to boil a mixture of hydrocarbons (propane and isobutane). The cooled geothermal fluid then goes to injection wells and the hydrocarbon vapor drives turbines and is condensed and returned to the heat exchanger. In neither case is necessary to discharge geothermal brine to the surface. As far as emissions to the atmosphere are concerned, the Binary Cycle uses a completely closed system, whereas in the Flashed Steam Cycle some non-condensable gas may be produced from the steam fraction. However the amount is very small compared to the emissions caused by electrical generation fueled by fossil fuels such as coal, oil, or natural gas (see Table 3).

Table 3. Air Emissions from Electrical Power Plants in the USA, for the year 2000 (data from Kagel et al. 2005)

Air Emissions	**Carbon dioxide**	**Sulfur dioxide**	**Nitrogen oxides**	**Particulate matter**
[kg/MWh]				
Coal (average existing plant)	996	4.7	2	1
Oil	760	5.5	1.8	not available
Natural Gas	551	0.1	1.3	0.06
Average (all US Power Plants)	623	2.8	1.3	not available
Geothermal (flashed steam)	27	12.3	0	0
Geothermal (binary)	0	0	0	0

3.2 Research Accomplishments Related to Geothermal Drilling

There are many research opportunities associated with drilling for high-temperature geothermal resources. For example, in the USA the Department of Energy (DOE) carried out a basic research program involving drilling in geothermal areas and thermal regimes for more than a decade (Wollenberg et al. 1989). As part of this program, a partially cored well 3.2 km deep, in southern California in the Salton Sea geothermal field, produced 360 ^{o}C metal- rich, hypersaline brines (salinity > 20 wt.%) from sediments metamorphosed to lower amphibolites facies, and containing abundant hydrothermal ore minerals in process of formation (Elders and Sass 1988). The US Department of Energy also had a vigorous research program on “Magma Energy” that explored the possibility of producing geothermal energy directly from molten rock at depth (Mock et al. 1997).

This program even planned the drilling of a deep well to reach magma and began drilling in the Long Valley Caldera, located on the eastern side of the Sierra Nevada Mountains of California. This caldera was produced by a catastrophic eruption about 760,000 years ago and had recently shown signs of unrest with earthquake swarms and ground deformation, accompanied by increased CO_2 gas emissions and changes in hot springs in the region. It was speculated that the caldera could be underlain by a shallow magma chamber as large as the one that was responsible for the caldera-forming eruption. Analysis of microgravimetry and deformation data indicates that the composition of the shallower source apparently involves a combination of silicic magma and hydrothermal fluid. An area of magma intrusion was identified beneath a resurgent dome near the center of the caldera. A borehole was sited there designed to explore geothermal energy extraction at high temperatures from near the magma chamber. The first phase of this magma energy drilling project reached a depth of only 780 m. in 1989, when the DOE’s priorities changed and drilling by the magma energy program was terminated. In 1991 this borehole was taken over and deepened to 2.3 km depth, as the “Long Valley Exploratory Well” (LVEW), designed to explore the nature of the caldera and its shallow geothermal potential.

This demonstrated that downhole temperatures were too cold for economically viable geothermal power generation. However in 1998 this well was deepened to 3.0 km depth for scientific purposes, with participation by the ICDP. In 2003 the United States Geological Survey converted the LVEW into a geophysical observatory to measure seismicity, deformation, and fluid pressure in the caldera. Studies of the data and samples from this well, coupled with extensive geophysical studies indicate that in addition to a relatively shallow (7-10 km) source beneath the resurgent dome, there exists a deeper (approximately 15 km) source beneath the south moat of the Long Valley caldera. Thus a well designed for geothermal exploration advanced basic scientific studies of volcanology and volcanic hazards in a large, young, silicic caldera (Sorey et al. 2003; Hill et al. 2002).

Although much geothermal research is of an applied nature, such opportunities for important basic research will continue. Today some of the most interesting new scientific issues occur in the development of "*enhanced*" or unconventional geothermal resources. Enhanced geothermal resources are geothermal reservoirs that require engineering modification to improve their output and economics. For example, one type of enhanced geothermal resource is "Hot Dry Rock" that depends upon the natural radioactivity of granites as a source of heat. Although radioactive granites may be hot, their intrinsic permeability and fluid content is normally too low to sustain useful rates of fluid flow. To extract useful heat the permeability of such granites has to be enhanced by hydraulic fracturing, creating fluid pathways connecting injection and production wells.

Currently the world's largest enhanced geothermal resource investigation is the research and development program being carried out at Soultz-sous-forêts in the Rhine Graben of France since 1987 (Baumgärtner et al. 2005). The target there is heat in the granitic basement beneath 1400 m of sedimentary cover where temperatures exceed 200 ^{o}C. This work provided ample research opportunities in petrophysics, and techniques of detecting and mapping induced seismicity, for example. A pilot plant of 6 MWe installed capacity will utilize hot water from two production wells and an injection well, each approximately 5 km deep. Another promising Hot Dry Rock project is underway in South Australia where temperatures exceed 290 ^{o}C at 5 km depth in granitic basement in the Cooper River Basin (Wyborn et al. 2005). Because of the additional costs of enhancing the permeability of such systems, at present there are no commercially operating hot dry rock systems. However, radioactive granites are widespread in the continental crust, and, if this approach proves to be economically viable, projects of this kind will proliferate, creating new research drilling opportunities to study heat flow, and permeability and fluid flow in crystalline rocks, etc.

In contrast, currently operating commercial geothermal power plants rely on natural permeability, and almost all are associated with young volcanic terrains (see the Chapter on "Volcanism and Thermal Regimes" in this volume). For example, in Italy the geothermal systems of Larderello, Travale, and Radicodoli, with a combined installed generating capacity of approximately 790 MWe produce about 25% of the electricity needs of the province of Tuscany (Capetti and Cepatelli 2005). At Larderello the explored area is 250 km^2 and a total of 180 production, exploration and injection wells produce 850 kg/s of superheated steam at temperatures of 150 - 270 ^{o}C, largely from permeable layers in a metamorphic basement that is overlain by Miocene carbonate marine rocks. During the period 2000-2004, 21 new geothermal wells were drilled in Tuscany, five of them deeper than 4 km. The results suggest the existence of a deep geothermal system with an area of 400 km^2 that underlies the Larderello Travale/Radicodli areas. Within this hydrothermal system at 3000 m depth temperatures are in the range of 300–350 ^{o}C, and fluid pressures are 6-7 MPa. A deep exploration program, involving 3 D seismic studies and 11 exploration wells deeper than 4 km, is underway that could provide numerous opportunities for scientists concerned with research on hydrothermal systems, if suitable collaborations between the scientific community and the Italian electric power industry can be developed (Capetti and Cepatelli 2005).

An excellent example of collaboration between government, industry and the scientific community that extended conventional geothermal resource investigations into new regimes of temperature is shown by one of the most interesting, and ambitious, scientific drilling projects of the last decade. Although hydrothermally altered rocks and contact metamorphic aureoles are exposed in mines and outcrops, for the first time this project allowed direct observation and sampling of the processes of their formation and the coupling of magmatic and hydrothermal processes. The project, designed to investigate deep geothermal resources, was funded by the Agency of Industrial Science and Technology (AIST) of Japan and involved scientists and engineers of the New Energy and Industrial Technology Organization (NEDO – a government agency), the Japan Metals and Chemicals Co., and university scientists. This was the 3.7 km deep exploratory borehole at Kakkonda, in the Hachimanti Geothermal Field, Iwate Prefecture, Japan, that penetrated into a cooling granitic intrusion (Muraoka et al. 1998). This well penetrated an entire shallow hydrothermal convection zone, an entire contact metamorphic aureole, and part of a neo-granitic pluton (tonalite with a K-Ar age of 0.19 Ma) that is the heat source for the hydrothermal system. The shallow hydrothermal system is developed in Holocene to Miocene volcanic and intrusive andesitic rocks and shows a boiling point controlled temperature profile down to 3100 m depth, where a 380 ^{o}C temperature occurs. At that depth and temperature, a transition from brittle to ductile conditions was observed and the temperature gradient became conductive. Temperatures reached >500 ^{o}C at 3729 m (Muraoka et al. 1998). At the bottom of the borehole the permeability was low and the hole was subject to plastic deformation. For this reason the drill hole was completed as a production well in a shallower part of the hydrothermal system.

This borehole represents a number of firsts that extended the range of geothermal investigations worldwide. The bottom hole temperature of >500 ^{o}C is the highest so far measured in any drilling project, except for the rare occasions when still-molten lavas have been drilled. For instance, in 1973, a newly-erupted molten mugearite lava (1060 °C) was drilled on the island of Heiamey, Iceland, and a heat exchange system was constructed for a district heating system that was used over a decade. In another example, a 100 m deep drill hole penetrated the crust of a still molten lava lake at Kilauea Iki, Hawaii (Hardee et al. 1981). The borehole at Kakkonda reached temperatures higher than the boiling point depth curve and entered a subsolidus cooling pluton. It was possibly also the first geothermal well to penetrate the brittle-ductile transition (Muraoka et al. 1998). It is theorized that, in high-temperature geothermal systems, the main constraint on the maximum depth of hydrothermal convection is the control on permeability exerted by the transition from brittle to ductile behavior (Fournier 1999).

3.3 Current Research on Unconventional Geothermal Resources

The main challenge facing the geothermal industry today is to make geothermal energy more available by improving its economics. One approach to achieve this goal is to reduce the costs of drilling geothermal wells by improving the technology of drilling. Because of the combination of high temperatures, abrasive rocks, and corrosive fluids, geothermal wells are expensive to drill relative to oil or gas wells of the same depth. Improving drilling technology would not only benefit industry but also reduce the costs of scientific drilling. The other approach to improving the economics of geothermal resources is to increase the power outputs of geothermal wells relative to the costs of drilling them. This is the approach being taken by the Icelandic Deep Drilling Project (IDDP), a joint venture between the Icelandic geothermal industry and the Icelandic government (Fridleifsson and Elders 2005). Because the IDDP could serve as a case study for industry/government/science collaboration, its history and current status is described here at some length.

3.3.1 The Iceland Deep Drilling Project

Currently high-temperature geothermal wells in the worldwide geothermal industry produce a two-phase mixture of water and steam at temperatures typically in the range of 200-320°C. The principal aim of the IDDP is to investigate enhancing the economics of high-temperature geothermal resources by utilizing *supercritical* geothermal fluids. Figure 2 shows how the boiling point of pure water is elevated as pressure increases until the critical point (CP) is reached at a temperature of 374.15^{o} C and a pressure of 22.21 MPa. The density of water decreases when ascending the boiling point curve towards the CP, whereas the density of steam increases until at the CP their densities are equal and only a single phase, supercritical fluid, exists. As shown in the figure, the effect of dissolved salt is to elevate the pressure and temperature of the CP, whereas the effect of a dissolved gas, such as CO_2 is to lower its temperature (Bischoff and Rosenbauer 1984). Supercritical phenomena are of great scientific interest because of the role they play in heat and mass transfer, metamorphism and ore genesis (Norton 1984). Although supercritical phenomena are very important in nature, the physics and chemistry of supercritical geothermal fluids in the Earth's crust are poorly known, and there have not yet been any attempts to put natural supercritical fluids to practical use.

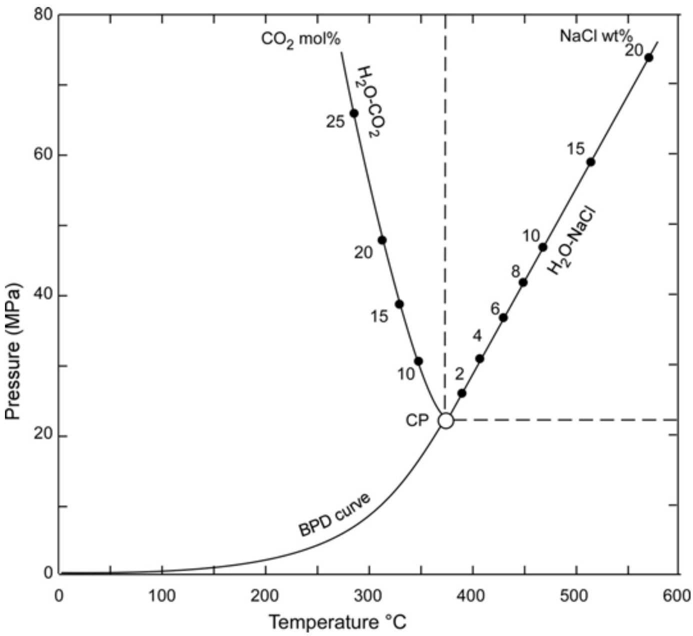

Fig. 2. The effects of dissolved NaCl and CO_2 on the pressure and temperature of the critical point of water (compiled from data of Bischoff and Rosenbauer 1984).

Superheated steam produced from a fluid initially in the supercritical state will have a higher enthalpy than steam produced from an initially two-phase system, but, in addition, large changes in physical properties of fluids occur near the critical point. Orders of magnitude increases in the ratio of buoyancy forces to viscous forces occur that can lead to very high and fluctuating rates of mass and energy transport (Norton and Dutrow 2001). Similarly, because of major changes in the solubility of minerals above and below the critical state, supercritical phenomena play a major role in high temperature water/rock reaction and the transport of dissolved metals (Fournier 1999). Hitherto, study of such supercritical phenomena has been restricted to either small-scale laboratory experiments or to investigations of "fossil" supercritical systems exposed in mines and outcrops. Furthermore mathematical modeling of the physics and chemistry of supercritical fluids is hampered by a lack of a reliable thermodynamic database over the range of temperatures and pressures of the supercritical state, particularly for saline fluid compositions.

Modeling carried out as part of a two-year long feasibility study by IDDP, completed in 2003 (available at http://www.iddp.is), indicates that, relative to the output from conventional geothermal wells 2.5 km deep, a large increase in power output per well is likely if fluid is produced from a reservoir hotter than 450°C (Albertsson et al. 2003). A typical geothermal well in Iceland, 2.5 km deep, costs about 4 million USD to complete, and yields fluids in the range of 200-320°C, an output sufficient to generate to 3-15 MW of electric power, depending on P-T conditions and the flow rate. For a rough estimate of the electric power output that may be expected from a deep IDDP well, a comparison with a conventional geothermal well is instructive (Albertsson et al. 2003). A conventional well that produces dry steam only (235°C), at a wellhead pressure of 2.5 MPa and a downhole pressure of 3.0 MPa, will yield approximately 5 MW of electric power if the volumetric rate of inflow to the well is 0.67 m^3/s. An IDDP well tapping a supercritical reservoir with temperatures of 430–550°C and pressures of 23–26 MPa may be expected to yield 50 MW of electric power given the same volumetric inflow rate of 0.67 m^3/s. Thus an IDDP well could yield a tenfold improvement in power output relative to a typical conventional well. However, to produce supercritical fluids requires drilling deeper than 4 km to reach temperatures >450 °C. The feasibility study also concluded that drilling a well 5 km deep to reach temperatures of ~450 °C could be done, but such a deep production well would cost about 9 million USD. Drilling such wells to explore for this unconventional geothermal resource would also allow experiments in permeability enhancement to be conducted.

From the outset the IDDP industrial consortium has been receptive to including scientific studies in the IDDP, provided that any additional costs thus incurred are met by the scientific community. With the financial support of the ICDP, international workshops were held in 2002 to organize a science program. The feasibility study identified three locations where supercritical fluids were likely to exist at drillable depths in the geothermal fields at Reykjanes, Nesajavellir, and Krafla (Fig. 3). The active rifting and volcanism in Iceland is usually regarded as being due to its location at the coincidence of the spreading centers of the Mid-Atlantic Ridge and a mantle plume (Conrad et al. 2004). Iceland is the largest landmass straddling a mid-ocean ridge and lies at the center of an actively forming Large Igneous Province stretching from Greenland to Scotland (Fig. 3). Within the central zone of Holocene rifting, the rocks nearest the surface are hyaloclastites and basalt flows, which overlie sheeted dike swarms. These undoubtedly pass downwards into gabbro intrusives that are the likely heat sources for the numerous active hydrothermal systems in the central rift in Iceland (Fig. 4). These rocks in turn should be underlain by ultramafic rocks typical of the upper mantle. With few exceptions, such as the Oman Ophiolite, ocean crust is not usually available to study at outcrop. However, drilling at sites in Iceland offers the advantage of permitting drilling into an ophiolite sequence on land, and to directly study *active* formation of ocean crust.

In late 2003 a member of the industrial consortium, offered one of its planned exploratory/production wells located on the Reykjanes peninsula for deepening by the IDDP. This borehole was completed to 3.1 km depth in February 2005 (Elders and Fridleifsson 2005). However, it became blocked during a flow test in November 2005 and, during attempts to recondition it, a drill head assembly sheared off and so the hole was abandoned in February 2006. This required a change of plan and the decision was made to move operations to Krafla, one of the central volcanoes shown in Fig. 3, as the site of the first deep IDDP borehole.

This location is a volcanic caldera with higher temperature gradients and more recent volcanic activity than Reykjanes. A recently completed production well there had temperatures of up to 340^{o}C at 2.1 km depth. At an adjacent site the IDDP will rotary drill and spot core, and case a borehole to 3.5 km depth, then deepen it to 4.5 km, using continuous wireline coring for scientific purposes, and then attempt a flow test from the deepest, hopefully supercritical, portion of the well. The science team has obtained awards of 3 million USD from the US National Science Foundation, and 1.5 million USD from the ICDP to obtain drill cores and data for scientific studies as part of the IDDP. Three industrial partners and the Icelandic government are each contributing about 4 million USD to the project and a formal contract to this effect was signed in April 2006.

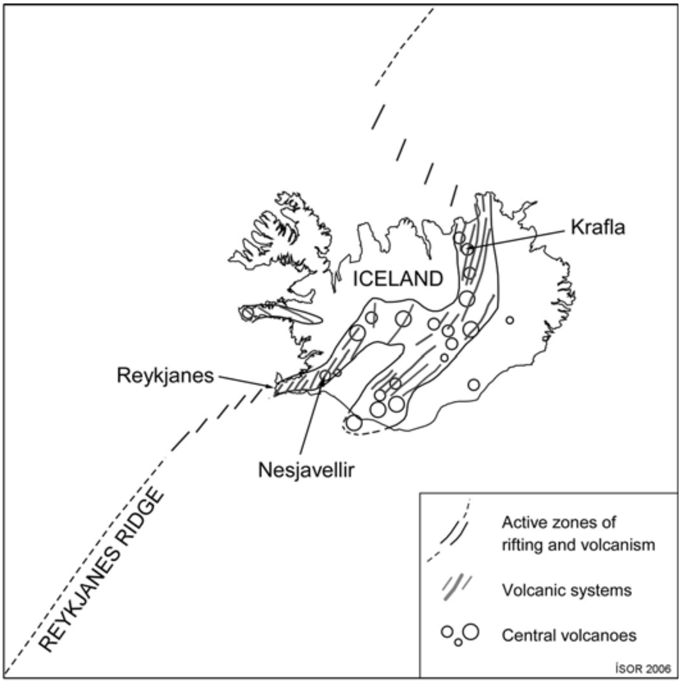

Fig. 3. The location of Iceland on the Mid-Atlantic Ridge, showing the zones of active rifting and volcanism, and the three hydrothermal systems being considered as for sites for 5 km deep boreholes.

In addition to exploring for new sources of energy, this project will provide the *first opportunity worldwide* to investigate the deep, high temperature reaction zone of a mid-ocean ridge hydrothermal system, which has been long-standing goal of the Ocean Drilling Program. This drill site is ideally situated for a broad array of scientific studies involving reactions between basalt and hydrothermal fluids at high temperatures, reaching supercritical conditions, with hornblende hornfels, or amphibolite, facies grades of metamorphism. The flux of seawater through mid-ocean rift hydrothermal systems is an important component of lithosphere-hydrosphere interaction and a major control on the chemistry of the oceans. However, active processes in the deep, high-temperature, reaction zones that control fluid compositions have never before been available for comprehensive direct study and sampling. Drilling at Krafla represents the first stage in understanding high temperature basalt alteration in an active geothermal system. Follow-up drilling on the Reykjanes peninsula will allow comparison to a of high temperature system with seawater salinity, and provide a direct on-land analog of black smoker vents.

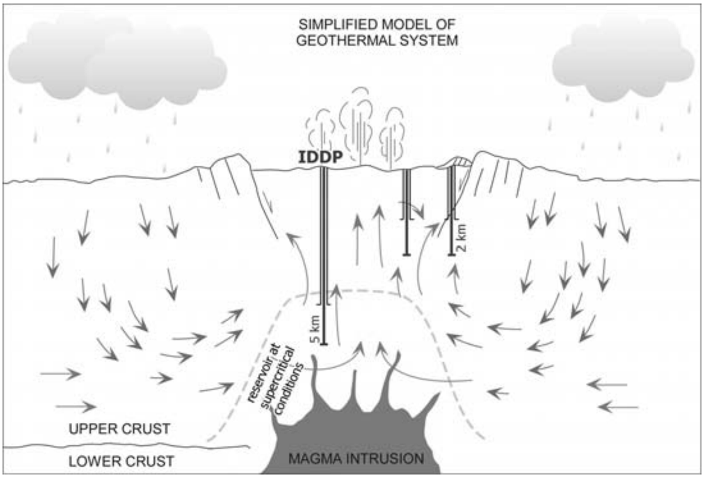

Fig. 4. A schematic diagram of the crust in the central rift zones of Iceland showing a hydrothermal system heated by intrusions. Heat sources are thought to be commonly at 5 –10 km depth. The IDDP will explore the supercritical zones adjacent to still hot or molten intrusions.

The international science community has made investigation of these hydrothermal systems at mid-ocean ridges a high priority, as demonstrated through funding of programs like RIDGE, InterRidge, and MOPAR, and by the extensive scientific drilling conducted by the Ocean Drilling Program (DSDP/ODP). Among the least understood, least accessible, but most crucial, aspects of lithosphere-hydrosphere interaction are the formation of ocean crust, and the nature of thermal boundary zones and cracking fronts, and the transition from subcritical to supercritical conditions in the hydrothermal environments near mid-ocean ridge magma chambers. These high-temperature research targets have hitherto been largely beyond the technical capabilities of the ODP. One of the great successes of ocean drilling, DSDP-ODP Hole 504B, near the Costa Rica Rift, is the deepest comparable hole in ocean crust. However, it took eight cruise legs stretched over many years to reach only 2.1 km depth and temperatures ~ 160°C (Gable et al. 1995). The data from Hole 504B illuminated, but did not resolve, the arguments about how well an ophiolite model explains the seismic velocity layering of ocean crust (McClain 2003; Alt and Teagle 2000). Is the boundary between layers 2 and 3 a contact between sheeted dikes and gabbro, a stress change, or a product of hydrothermal alteration? This zone has been a consistent but challenging goal of scientific drilling. McClain (2003, p. 181) wrote “*In the end, the only true test of the ophiolite model would be to drill into undisrupted crust that was generated on a* *non-rifted ridge. It is unlikely that we will see this done in the immediate future….*". The 4-5 km deep IDDP drillholes may be the opportunity McClain sought.

In contrast to the relatively limited results obtained from Hole 504B, the first deep IDDP Drillhole will produce fluid samples from the flow tests as deep as 4.5 km and pressure/ temperature/ flow-meter logs over the whole drilled interval. Drill cuttings and spot coring down to 3.5 km depth, and 1.0 km of continuous drill core from as deep as 4.5 km should reveal the integrated record of basalt-water interaction recorded in these rocks. Depending on the fluid chemistry and pressure, the drilled interval between 3 and 4 km should approach pressure-temperature conditions similar to those of the source region for black smokers sampled on oceanic spreading centers. Coring below 4.0 km is designed to penetrate into supercritical fluids which couple black smoker hydrothermal systems with their magmatic heat sources. These environments have never before been available for comprehensive direct study and sampling. The broader implications of the IDDP are twofold; scientifically it will permit a quantum leap in our understanding of active hydrothermal processes that are important on a global scale, and secondly, if the industrial aims are successful, the resulting technology could have a major impact on improving the economics of high-temperature geothermal resources in volcanic terrains worldwide, and thereby make accessible larges sources of deep geothermal energy that hitherto have not been developed.

3.4 Future Trends in Scientific Drilling for Geothermal Resources

The scope of drilling "conventional" geothermal wells is increasing globally and providing numerous worthwhile research opportunities. However, much of the most important, ground-breaking research will be associated with deep, high-enthalpy resources. For example, the long-term plans of the IDDP are to drill 4 to 5 km deep exploration wells for supercritical resources in other high-temperature geothermal fields in Iceland, such as Nesjavellir and Reykjanes (Fridleifsson and Elders 2005). The ambitious drilling plans for deep drilling at Larderello, Italy, mentioned above, will also provide exciting research opportunities. Similarly, at the Potsdam conference Hirofumi Muraoka described proposals to apply the results of the Kakkonda drilling project and drill 5 km deep boreholes along the young volcanic arc of northeastern Japan. The aims are to clarify the nature of the brittle-plastic transition and the depth of fracturing, to investigate the nature of fluid circulation and the chemistry of the fluids, to determine the nature of zoned magma chambers beneath calderas, to measure strain absorption along the volcanic front of an island arc, and finally to explore the economic potential of these deep high-temperature geothermal resources. Similar investigations could be carried out wherever young volcanic rocks occur. One example where the connection between magmatic and hydrothermal systems might be explored by drilling is the Mutnovsky volcano in Kamchatka (Kiryukhin and Eichelberger 2005: see Chapter on "Volcanism and Thermal Regimes" in this volume). As research drilling targets move to higher and higher temperatures we will learn more and more about the hydrothermal/magmatic interface and ultimately attempt to drill directly into magma.

4 Industry Coupled Scientific Drilling

Joint ventures with industry and government in scientific drilling have obvious advantages. For example, industrial partners can expedite unique access to scientifically important sites and contribute their considerable engineering skills and operational capabilities, including drilling and downhole logging, etc. Similarly, industrial partners may contribute scientifically important background data from geophysical surveys and from previous drilling necessary to refine research targets and reduced operational risks. Collaboration could involve cost-sharing, or perhaps deepening a borehole well drilled for a different purpose, as was done in Long Valley, California. Industry participation in scientific drilling programs can permit far-reaching contributions to basic research and education and create opportunities for scientists to become involved in ambitious projects that have budgets larger than can be funded by the usual agencies that fund academic science, as is the case in the Iceland Deep Drilling Project.

In turn, the industrial partners can benefit from strong scientific contributions from agencies such as ICDP, which can be far-reaching and expand opportunities for innovation. ICDP researchers often are world leaders in their disciplines and able to access unique analytical facilities and initiate novel research projects. These scientists can contribute a longer term perspective on research beyond the normally shorter term objectives of industry. This perspective can be of critical importance in the context of natural system processes such as global climate change and other important environmental issues.

While collaboration between science and industry has clear advantages, there are also some significant challenges that must be overcome in order for an industry-coupled scientific drilling project to be successful. For instance, the schedule and phasing of milestones for a large research project might be dictated by broader business and economic concerns. Similarly, priorities for siting boreholes must be negotiated, together with business issues such as liability, commingling of funds, and legal agreements. These issues must be solved on a case by case basis and responsibilities must be negotiated and clearly defined in a spirit of mutual cooperation.

5 Summary and Recommendations

Natural resources are essential for the continued prosperity of modern civilization and scientific research on the origin and distribution of natural resources has been, and should remain, a key component of the ICDP's plans. However drilling for natural resources is the *raison d' être* of the worldwide drilling industry, an enterprise with which the ICDP cannot, and should not, compete. ICDP's limited funds should not be used in ways that subsidize, or replace, drilling that is more properly the domain of industrial and government entities concerned with the development of natural resources. The guiding principle that should shape the role of the ICDP with respect to natural resources is that, where possible, ICDP should investigate broad, over-arching, research questions that are not routinely addressed by industry and should rank highly research proposals that have that have a potential for positive contributions to environmental problems.

Thus the ICDP should be both proactive and selective in considering drilling related to natural resources. Within this realm of natural resources, the topic of new or unconventional energy resources should be given priority in view of the increasing demands for environmentally benign sources of energy by the world's burgeoning population. Two examples where ICDP has had success in contributing to the science behind meeting the need for alternative sources of energy are the Mallik 2002 Production Research Well Program, that investigated natural gas hydrates in permafrost, and the ongoing Iceland Deep Drilling Project, a long term geothermal research project that is exploring the supercritical fluid regime, intermediate between the known hydrothermal domain and the magma-hydrothermal interface. Apart from both these projects being energy-related, they have in common the fact that they involve substantial collaborations between industry, government agencies, the earth science community, and the ICDP.

Given the very diverse nature of natural resource drilling, the Natural Resources Panel urges the ICDP in the next decade to take advantage of the considerable potential that exists for collaboration with industry. Collaboration could take different forms, such as straightforward cost-sharing, or taking cores or logging in a well being drilled for different purposes, or deepening a borehole already drilled, or instrumenting an industry borehole as a down hole geophysical observatory. Joint ventures in scientific drilling with the natural resource industry have obvious mutual advantages. Raising the profile of ICDP within the natural resources sector should be a priority so that more cooperation between government, industry and the scientific community can be encouraged. This might be done as follows: (1) The ICDP could put more emphasis on outreach activities to industry and to professional societies whose members are drawn from the natural resource industry. A serious effort should be made to encourage industrial organizations to join the ICDP as full members. (2) The ICDP could hold workshops dedicated to the general topic of “fostering closer collaboration between science and industry”. This could consider (a) the resource sectors are best suited to such collaboration and the themes should be priorities for the future, (b) the unique issues raised by collaboration between industry and scientists (such as legal and liability agreements), (c) the policy concerning dissemination of data and confidentiality. (3) Scientists could be encouraged to develop working relationships with industrial organizations. This possibility should be mentioned in the annual call for proposals by the ICDP.

By partnering with industry on specific drilling projects the ICDP could be a catalyst to encourage novel drilling-related research on natural resources, particularly in the area of unconventional sources of energy. At the same time, there are many opportunities in this area for ICDP to fulfill the mission of addressing broad over-arching research questions that are not routinely addressed by industry and which have potential for making positive contributions to solving the large scale resource and environmental problems faced by society.

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