# icdp primer

INTERNATIONAL CONTINENTAL SCIENTIFIC DRILLING PROGRAM

## planning managing & executing continental scientific drilling projects


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**Imprint**

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# Preface

Present day system Earth research utilizes the tool 'Scientific Drilling' to access samples and to monitor active processes that cannot be addressed by other means. Unlike most laboratory experiments or computer modelling, drilling projects are massive field endeavours requiring concerted interactions of researchers, engineers, and service providers. In the framework of the International Continental Scientific Drilling Program, ICDP, almost sixty drilling projects have been developed, from multi-year big research programs to short, small-scale deployments such as lake drilling projects. ICDP has supported these projects not only through grants covering field-related costs, but also through a variety of scientific-technical services and support, as well as active help in data management, outreach and publication. These services are described in this booklet. Due to its instructional character, we call it the *ICDP Primer*.

The Primer is organized along a drilling project development scheme in ICDP. After introductory notes (**Chapter 1**) it addresses the formalities of a scientific drilling project (**Chapter 2**), including proposal writing in ICDP with the pre-, workshop and full proposal cycle, funding principles, policies and deliverables. The following paragraphs are devoted to the professional management of drilling projects (**Chapter 3**) and rationalize professional administration and supervision of complex, costly drilling missions. The subsequent **Chapter 4** provides insight in project execution from site survey, drilling planning, sample handling, data management, downhole logging and finally monitoring in boreholes. Conclusively, training, outreach and capacity building and communication with media are described (**Chapter 5**). Last but not least, the scientific-technical services by ICDP and its Equipment Pool are integrated in this section, too. A glossary and a comprehensive number of addenda assists readers with further explanations and practical details (**Supplements**).

Key steps and important challenges in continental scientific drilling have been distilled into this best practice brochure. The authors are members of the ICDP Operational Support Group (OSG) or scientists of ICDP projects. The OSG is based at the GFZ, the German Research Centre for Geosciences in Potsdam. It acts as Executive Agency of ICDP and provides expert manpower through the OSG. The OSG organizes drilling projects, provides tools and services and supports project scientists in all aspects of the preparation and execution of a drilling scheme. Their expertise is the base to train participants of upcoming drilling projects through annual Training Courses and individual training programs. The community at large supports these educational efforts as several individuals serve through providing course elements embedded in the ICDP training efforts.

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# ICDP Primer

*A guidebook for scientists planning and executing a drilling project*

*(or: the perfect recipe for a five-star drilling project)*

**CHAPTER 1**

# Introduction

**Ulrich Harms**

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

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

**Membership Benefits**

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

The ICDP was formed in 1996 and has grown to include more than 20 participating countries across the world plus UNESCO. ICDP organizes peer evaluation of project proposals and combines the annual financial contributions of its members to part-fund research projects. The benefits of being a member are numerous. Scientists and engineers can apply for funding through proposals, they can lead projects seed-funded by ICDP, and they have priority access to data and sample repositories during the moratorium phase. Workshops, training, and education are offered to member countries and the services of the ICDP Operational Support Group and the ICDP Equipment Pool can be utilized. Furthermore, and most important for national funding agencies who usually lead the membership and raise the annual fee, the members possess a seat and a vote in the decision-making ICDP panels and can determine the policy, the funding strategy and individual grant choices. ICDP funding typically covers 10-50% of the full cost of a drilling project, but more importantly provides leverage for project teams to generate other funding. ICDP proposals undergo a strong and independent evaluation by globally selected expert scientists, the Science Advisory Group (SAG), and are further evaluated by experienced project managers from member countries, the Executive Committee (EC), based on clearly stated criteria of scientific merit and societal relevance. The Assembly of Governors (AOG) provides oversight through representatives of the funding agencies allocating project grants. Thus ICDP-approved projects provide a basis for additional high-quality scientific research. For example, continued work on samples and data collected during ICDP projects typically leads to a large number of scientific publications and promotion of early-career scientists. The economic factor of ICDP investments is also noteworthy, as local drilling and service companies may be contracted for ICDP projects, allowing some investments to flow back into the country.

**ICDP Co-Funding**

Once a drilling project has been approved within the program and the amount of ICDP co-funding has been allocated, the proponents work to secure additional funding, usually from their national funding agencies. Thus, the program's policy of supporting international teams is vital, in that it ensures there are a range of funding opportunities for each project. This 'seed money' philosophy, in combination with the excellent in depth-reviews by the ICDP Science Advisory Group, helps to 'open doors' and provides proponents with the opportunity to seek the necessary co-funding from additional sources. ICDPs share is devoted to all field operations only, so that third-party sources need to be tapped that cover operations and the scientific laboratory work in the home institutes of the science team members. Designated ICDP funds are held at the host agency, the German Research Centre for Geosciences (GFZ), until enough money is accumulated to run the project.

The co-mingling of funds is one of the greatest success stories of the ICDP. A look back at the total funding obtained over the past more than two decades illustrates that ICDP's share per project, despite substantial variation, averages about 20% of the total operational costs (Fig. 1.1). So far, ICDP has invested about US$ 54 million in more than 57 projects, whilst an additional US$ 220 million has been raised from various third-party sources.


*Fig. 1.1: ICDP funding share versus total project budget for 57 past ICDP projects*

**Realization of an ICDP Project**

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

An important linkage of the ICDP exists to the International Ocean Discovery Program, IODP. Despite targeting two distinct geographical domains on Earth, scientific continental and ocean drilling are strongly aligned in their scientific objectives by having access to critical geological records attainable only by sustained and innovative drilling strategies. Through concerted efforts in Land-to-Sea (L2S) drilling major scientific breakthroughs in several challenges to humankind can be made. Combined scientific land and ocean drilling will emphasize transects from the ocean basins onto the continents, in research areas near and along coastlines, enabling innovative collaborative drilling campaigns from land to sea.

Proposal writing guidelines and proposal submission specifics are available from the ICDP website in the section **Proposals**. There are also subdivisions on the **review process** and the **review criteria** used by ICDPs independent review panel, SAG. For Land-to-Sea applications both programs, ICDP and IODP will handle the submission and review process. In any case, the OSG is available to support the development of proposals to ICDP during all phases.

**Operational Support Group**

The Operational Support Group is the key organizational element of ICDP conveying program continuity. In addition to providing financial support of drilling operations, the OSG offers scientific-technical help for ICDP projects with expert staff, tools, instruments and training. It has been developed to provide the essential know-how and materials at a scientific drill site for a transient period. After all, not every ICDP project team can be expected to develop the skills to plan, conduct and document a drilling mission on their own, starting from scratch. The PIs can rely on OSG to fill such gaps.

Continuity in operational support over the long term is important. The GFZ-German Research Centre for Geosciences funds a major proportion of the scientists, engineers and technicians who compose the core of the OSG. It is a separate organisational entity within Section 4.2 'Geomechanics and Scientific Drilling' of the GFZ. The funding of the core group of the OSG has been secured by the GFZ with currently 7 full time equivalents while ICDP supports currently 4.5 FTEs.

Overall, the OSG has the following support functions:

- Provides technical liaison to EC and SAG
- Acts as logistical interface between GFZ Finance Department and ICDPs Assembly of Governors (AOG) to facilitate financial planning
- Supports PIs in planning, design, management and execution of drilling projects
- Provides support for scientific and engineering drill-site operations
- Prepares funding agreements for each project authorized by EC
- Provides drilling equipment, downhole tools and field laboratory facilities
- Supports ICDP Workshops

- Provides support for field facility for core and sample description and management
- Provides training courses on scientific drilling as ‘training on the job’ or in preparation of future ICDP drilling projects
- Provides all data collected during each project through a data management system for ICDP projects, the mobile Drilling Information System (mDIS)
- Helps in the preparation of Initial Reports that describe drilling, engineering and sample and core parameters for each project through mDIS
- Develops, purchases, and maintains an Equipment Pool comprising scientific-technical instruments and tools for on-site use in ICDP projects

The OSG is subdivided into six working groups including:

- Drilling Engineering and Management – Santiago Ruben Aldaz Cifuentes
- Downhole Logging – Jochem Kück Simona Pierdominici, Marco Groh, Martin Töpfer
- Data Management – Cindy Kunkel, Katja Heeschen, Knut Behrends
- Education & Outreach – Thomas Wiersberg, Ursula Heidbach
- OSG Management - Ulrich Harms, Ines Thoss
- Executive Director and Panel Support – Carola Kögler

In addition, the OSG is supported by the Helmholtz Centre Potsdam - GFZ German Research Centre for Geosciences as Executive Agency of ICDP. Both, OSG and GFZ, are jointly represented in ICDP by the:

- Executive Director – Marco Bohnhoff

A detailed description of support, equipment and services offered by the OSG to all active proponents and PIs is described in the following chapters of this Primer. In addition, further information is available on the ICDP website in the Support section.

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# Project preparation in ICDP

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## 2.1 Proposals and project cycle

Scientific drilling projects often start when the lack of appropriate samples and data from depth drive the idea to drill and when at the same time sufficient information exists to justify preliminary siting and depth determination for boreholes. If the science team is international and a question of global significance and societal relevance is addressed, a Pre-Proposal to the ICDP will serve to get a profound scientific evaluation of such a project idea. Proponents will be informed if their proposal might be acceptable for funding by ICDP and what issues need to be tackled for the submission of a follow-up Workshop Proposal. The latter will seek financial support to assemble a broader team, discuss science, engineering and management of the drilling project, and strive to prepare the submission of a Full Proposal. Finally, when a Full Proposal has been accepted by ICDP a funding agreement will be signed with the Principal Investigators that determines the rights and duties of each party. If the necessary co-funding from other agencies has been acquired, schedules will be fixed and companies providing drilling and other necessary commercial services will be contracted.

As soon as the drilling operations are underway, scientists will start documenting data and samples in the field and perform first investigations. Detailed joint sample description, measurements and sampling by the science team in a core repository is used to prepare curation of samples and write reports. The data gained is under a period of confidentiality and only available to the science team for usually one or two years. Finally, individual research will be performed in the labs of the participating scientists once samples are chosen and distributed.

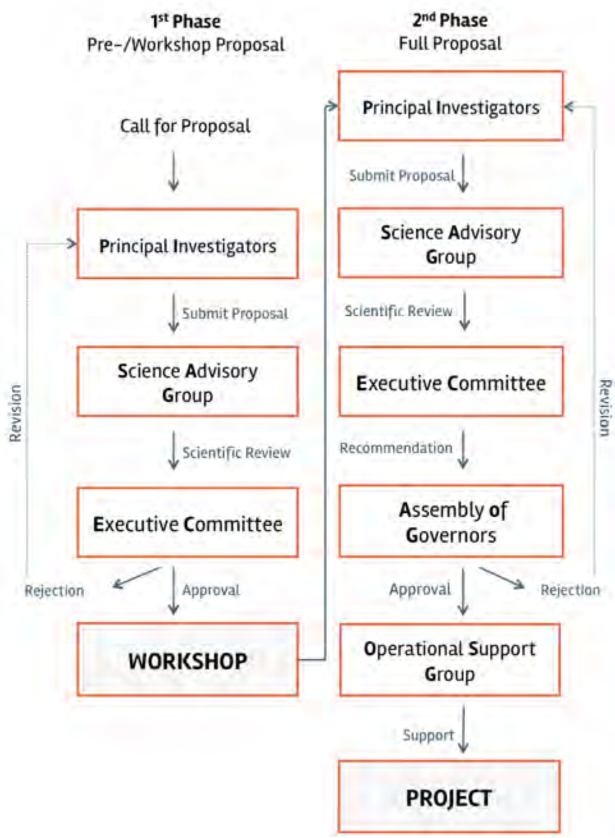


*Fig. 2.1: Scheme of ICDPs phased proposal flow; note that Phase 1 usually includes a Pre-Proposal and in addition a separate Workshop Proposal.*

After the end of field operations, initial description and curation, the laboratory work continues in most drilling projects for years. Once results from this work are available, a coordinated approach will be needed to publish initial scientific articles, detailed reports and results of single working groups.

**Phases of a scientific drilling project**

| Phase | Purpose |
|---|---|
| **Project Preparation** | |
| • Pre-Site Surveys | Select site(s) with best science for low costs |
| • Team Building | Select, motivate a group of scientists |
| • Pre-Proposal | Raise and test the idea |
| • Workshop Proposal | Internationalize, prepare a Full Proposal |
| • Full Proposal | Acquire funding, detailed plans |
| • Contracting | Secure funding, select service companies |
| • Training (e.g., mobile Drilling Information System – mDIS) | Prepare crew for duties before, during and after the actual drilling phase of the project; setup and train data and sample management workflows; conduct thorough expectation management on 'what', 'when', 'who', 'where', 'how much'; safety and hazard issues prior to any field operation |
| **Operation** | |
| • Engineering Operation | Drill holes, gain samples |
| • Scientific Field Work | Document samples and data from well |
| • On-site Science | Perform initial study on samples, compile |
| • Sample Curation | Operational Data Sets for science party |
| • Reporting "Drilling Report" | accompanied by initial reports<br>Process initial samples requests (sampling |
| • Outreach and Education | party) and store archive materials |
| **Scientific Work** | |
| • Lab- and office-based investigations | Examine, evaluate, test, model, develop research ideas |
| **Publication** | |
| • Workshop Report, Science Report | Publish the initial Science Report in 'Scientific Drilling` |
| • Scientific Articles | Publish the Operational Report including the Operational Data Sets |
| • Operational Report & Basic Data Set | Data set will also made available on ICDP website |
| • Sample Material and Curation | Publish articles in journals<br>Provide access to sample material post-moratorium in publicly accessible core repository (sample request forms) |

*Table 2.1: Phases of a typical scientific drilling project. Details vary from project to project and must be negotiated with all key players including scientists, contractors and funding agencies prior to any drilling operation.*

A general rule of thumb is that this time period of data-access exclusivity for participating scientists lasts from the time of data and sample acquisition for 2 years (as a reasonable time frame to publish at least preliminary data). However, this period needs to be clearly defined by the time the actual field measurements start, and preferably already upon signing the ICDP funding contract. After the end of the moratorium data sets gained will be published and sample materials is available for other scientists (see Table 2.1 for details).

## 2.2 Pre-Proposal, Workshop Proposal and the ICDP workshop

In ICDP a Pre-Proposal serves a group of scientists to have an idea involving scientific drilling thoroughly evaluated at an early stage without going through the more detailed stages of a Workshop Proposal. Preliminary proposals are not associated with funding but the ICDP review panel, the Science Advisory Group, will provide valuable hints and recommendations for a potential Workshop Proposal. Applicants should note that only projects of global scientific significance and with demonstrated international participation (or the prospect thereof) will be considered by ICDP. The existence of drilling-relevant site surveys, or a plan to acquire these, needs be discussed in the Pre-Proposal.

A Workshop Proposal serves a group of scientists from multiple ICDP member countries intending to submit a Full Proposal for scientific drilling to ICDP. The goal of an ICDP-funded workshop is to fully review the scientific motivation behind a project. This includes: why drilling is necessary, develop a preliminary drilling plan, management and research plan, discuss and compile site surveys or develop a plan on how to obtain these, and form an international cooperative science team with all expertise needed covered.

In ICDP, scientific drilling workshops have become a pivotal instrument to implement a drilling project. For the Principal Investigators (PIs) the approved ICDP workshop funds allow assembling experts in science and technology to create momentum towards the writing of a Full Proposal and to establish a team for applications, operations and investigations. At the same time the panels of the ICDP are involved early on. They can further and steer project ideas towards projects in line with the long-term scientific plans of the program and can adjust budgetary strategies.

The following paragraphs focus on site-specific workshops of ICDP that serve to develop a targeted drilling project. However, it is noteworthy that ICDP has also funded topical meetings, e.g., Fault Zone Drilling or Drilling for Microbiological purposes. Furthermore, ICDP supports also post-operational meetings for initial sample description, analyses and sampling in ongoing projects if proposed in the Full Proposal and if funds are available.

**Goals of site-specific drilling workshops**

The principal objective of an ICDP workshop is to prepare an ICDP Full Proposal. Once a Workshop Proposal has been accepted for funding by the ICDP boards, the PIs have the opportunity to design their meeting with the restriction that the budget provided by ICDP will be invested as planned in the proposal and for a broad international participation.

ICDP funds serve to cover a broad international participation of highly qualified scientists with an innovative disciplinary coverage including early career scientists. In order to invite such a broad participation, the PIs are obliged to publish an open Call for Participation. ICDP will announce the Call on the ICDP website and through social media channels. Another strategic purpose of the workshop will be the preparation of a Full Proposal to ICDP with best possible third-party funding in addition to the planned ICDP grant. Therefore, individuals efficient in funding acquisition from various national and international sources will be implemental for the success of a Full Proposal and should be invited to partake in the workshop. A collection of **Calls for Participation** is available on the ICDP website.

**Participation**

A successful workshop atmosphere can be created if the number of partakers is not too large so that everybody has the chance to speak up. Usually, 30 to 50 persons are present. A good mix of early career and established scientists guarantees the success of an ICDP workshop. A critical mass of leading researchers with institutional support is helpful to bridge long preparatory periods with supportive projects until drilling begins and to raise matching funds from other sources.

Once the 'Call for Participation' has been published, the number of applications submitted to the PIs can overrun the number of available slots for funding. In this case the PIs need to cover travel reimbursements to a lesser extend to ensure larger number of participants or exclude candidates; e.g., if expertise is covered by others already. Experts with knowledge in regional geology and in drilling should partake, too and from the perspective of complex and commingled funding acquisition funding agencies and experienced fund raisers may be welcome.

*Fig 2.3: ICDP workshop group photo; a creative atmosphere including breakout groups and site visits helps to develop the team spirit for a Full Proposal preparation and future interaction in the science team of a drilling project.*

The ICDP Operational Support Group (OSG) will support the preparation and conduction of the workshop and will make ICDP funds available according to the needs of the PIs but will not govern the planning. An OSG or ICDP panel member will usually attend the meeting. If applicants for workshop participation from the international community have to be rejected, the PIs will be asked to document the justification for such decision.

**Agenda, Duration, Venue**

A typical meeting (Fig. 2.3) is designed in a way, that all interested parties are introduced to the current state of knowledge and that at the same time the interest of each participant is briefly explained. Therefore, the first and probably second day is usually devoted to presentations of:

- the scientific goals according to the plans of the PIs and their Co-Investigators who wrote the Workshop Proposal
- the ICDP requirements and criterions to be addressed in a Full Proposal
- the technical feasibility of the planned drilling and downhole operations and the extent to which these are possible with the available funds
- local to regional geological and geophysical work relevant to the planned drilling program, followed by
- presentations of scientists regarding their expertise and specific interest in the drilling project in short oral presentations or posters
- status of pre-site survey in support to identify suitable drill sites and drilling depths

These presentations should be door openers for discussions and interactions between the distinctive science groups. They will also inspire participants to pinpoint knowledge gaps or deficiencies of key disciplines (modeling, microbiology, petrophysics, downhole logging) that need to be filled. Further essential debates focus on the completeness of pre-site surveys to define the drill site(s), the target depth(s), the core sections or if additional data needs to be acquired before a Full Proposal can be submitted.

These discussions can be subdivided in working groups if results are summarized in plenary meetings. Following these initial part (1 - 2 days) an excursion to the potential drill site(s) is appropriate. It will allow participants to get acquainted to the location, geology and infrastructure necessary for a drill site and field lab and will further foster informal face-to-face discussions in support of establishing communication and understanding in the group.

**0. Evening before meeting starts**
*Icebreaker*
**1. Day**
Welcome by PIs & Aims of the workshop
Synopsis talks on principle drilling issues
*Coffee break*
Regional geology, geophysics and site survey
*Lunch break*
Pre-drilling geophysics and geology needs
Drilling techniques and infrastructural needs
Geophysical downhole logging
*Coffee break*
Core and sample handling
Drill site investigations and special requirements such as for deep biosphere
*Dinner*
**2. Day**
Field trip
**3. Day**
Potential drilling sites (status, pros, cons), drilling techniques and target depths
*Coffee break*
Working groups
*Lunch break*
Working groups
*Coffee break*
Results of working group discussions
*Dinner*
**4. Day**
Definition of drilling target (site, depth, methods)
*Coffee break*
Possible costs and financial contributions
*Lunch*
Proposal writing and definition of tasks of each participant
*Departure*

*Fig. 2.4: Generalized workshop agenda*

A third and/or fourth day of the meeting should finally be designated:

- to define working groups
- to discuss and design the research program associated with drilling
- to set up the project management, the drilling plan, the management of the operations
- to select applicants for proposals to different funding agencies
- to summarize results and provide each participant with a clear role, responsibility and duty

Most ICDP workshops have been held in the vicinity of the envisaged drill sites and have dedicated a full day for a field excursion. Of course, a workshop near a drilling location only makes sense if this is within the meeting budget. However, if possible, in terms of costs and time, such field (or near-field) workshops have proven to be a very useful elucidation for the conduction of drilling planning meetings and consultations. In any case, a key prerequisite is the availability of facilities such as accommodation and seminar rooms through hotels or institutions nearby the location.

At the time of the writing of this Primer the COVID-19 pandemic has caused delays of many ICDP workshops because most PIs preferred to hold in-person-meetings. Accordingly, there is at this point not enough experience to report on the structure for online meetings.

**Defining roles and responsibilities**

The most important outcome of a drilling workshop is to create momentum for the formation of a science team that writes proposals to achieve full funding and that prepares and conducts the drilling project. Often in ICDP workshops, working groups were formed for different disciplinary and operational tasks; furthermore, individuals and groups are given the duty to spearhead fundraising missions towards various potential funding agencies, sponsors or industry at the same time. In other words, a workshop serves to design a structure for the different phases of a drilling project. Once the key scientific goals have been defined and the best possible funding opportunities identified, groups and group leaders can be formed to support the PIs.

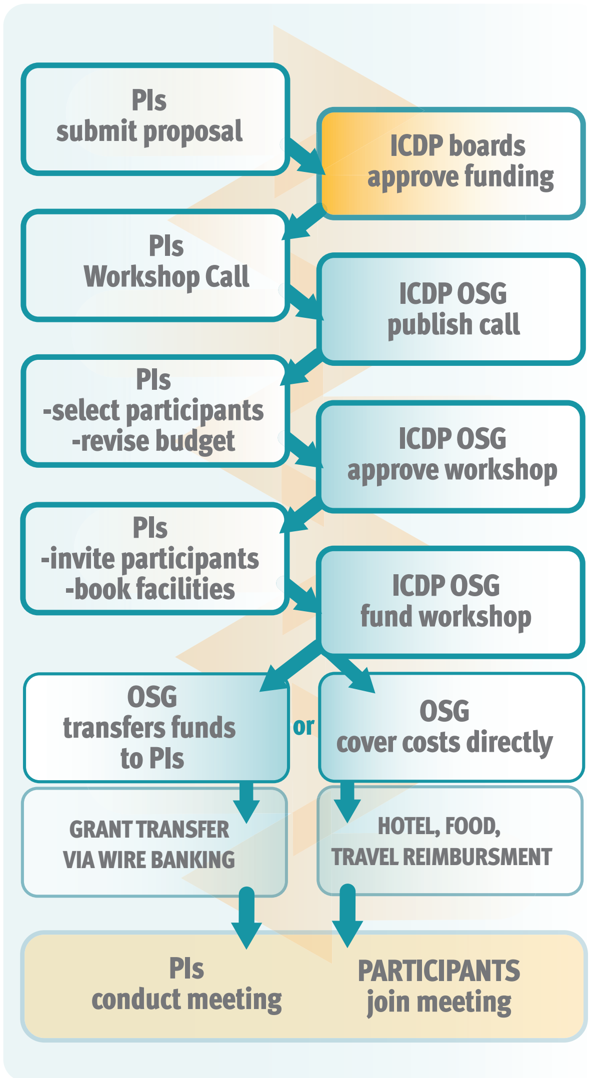


*Fig. 2.5: Administrative workshop flow*

**Administrative organization**

The OSG will make the ICDP workshop funding available once the PIs have revisited the budget plans and selected attendees for the meeting. Grant transfer can be initiated from ICDP to the PIs organization after a formal letter of workshop acceptance has been signed by the lead PI. In addition to the above-mentioned fund transfer, PIs can alternatively request OSG to cover costs for accommodation or catering directly with the contractors. Furthermore, OSG can reimburse travel costs of approved participants. For this purpose OSG is providing an ICDP travel expense claim form on the ICDP web page. PIs should make this form available to the participants during the workshop. A graphical abstract of the administrative steps is given in Fig. 2.5.

## 2.3 Writing of a Full Proposal

From a scientific point of view a convincing proposal outlines a clear idea of the project's goals and objectives, promises a significant progress in understanding the Earth and in developing the society. It convinces not only the peers of the specific subject, but also scientists and decision makers from other fields and regions.

**Prerequisites for success**

Fundamentals for success include a bright and novel scientific thought in Earth Science to study a process or test a hypothesis that is only accessible through drilling. In addition, the expected results should promise high impact in the broader science community and provide progress for the society at large. A proposal to ICDP should address such notions very clearly. In addition, the following prerequisites need to be laid out in a proposal to ICDP including:

- Drilling at sites of global scientific importance and societal relevance
- Excellent geophysical and geological site surveys to justify drilling target, drilling depth, and to reduce drilling risks
- Technical feasibility and budget realities
- Environmental and societal compliance
- Acceptance and support through national authorities early in the planning phase
- High degree of international cooperation in best possible science teams with excellent educational potential
- The scientific justification and drilling plans were agreed upon in a preceding joint ICDP workshop of the science team
- Well-structured and feasible project, data and sample management plans

**Organizational prerequisites**

ICDP only supports parts of the field operations of a project including drilling and drilling-related work. Therefore, ICDP-funded projects need to acquire additional financing from other funding agencies or industry. Funding for site survey and post-drilling science is not covered by ICDP and needs to be raised by the PIs. Accordingly, PIs have to orchestrate the interplay of national and international partners for project financing. Although this seems to be a difficult and time-consuming issue, many ICDP projects made very positive experiences and created several precedence cases of successful cooperation once a first major share of funding has been acquired, e.g., the ICDP funding.

A clear and transparent leadership of a project helps to establish a science team with a strong and continuous momentum during the usual multi-year duration of scientific drilling missions. The formation of an enthusiastic and diligent team and the combination of individual capabilities are major tasks for the PIs. The information pathways within a group and to the related organizations such as ICDP must be clear and remain intact and operative throughout the full project time. Excellent communication and management skills as well as planning competencies and experience of the project leaders with other large international Earth science projects are of paramount importance. Professional drilling project managers are often necessary to succeed. A drilling operation will benefit from international cooperation and support, but should also be rooted in the home institutes of PIs and within a broader national community. The complex multi-source funding needed for drilling requires that project team members need sustenance and backing on the broadest possible base. Early communication with colleagues, deans, universities, ministries, and authorities can help to pave the road towards timely, successful and wealthy drilling operations, especially for PIs from countries hosting the drilling project.

An outstanding group addressing all these requirements cannot succeed without good relationships to commercial service providers such as engineering consultants or drilling contractors. A Full Proposal to ICDP will need a drilling plan and include a detailed budget with reliable and justifiable numbers, which must be accepted by independent project reviews. Furthermore, sufficient contingency planning based on a critical risk analysis will provide a profound base for a sound proposal. The data needed for such considerations cannot be compiled without the support of drilling professionals.

**Chances**

Proposals to ICDP have a high rate of success if resubmissions are taken into account. About three quarters of the proposals that are submitted to acquire substantial funds (>$US100.000) for drilling are accepted for funding or have been invited to submit a revised proposal or an addendum. About 60% of workshop and Pre-Proposals have either received a grant to conduct a meeting or have been asked to develop their ideas further and to re-submit their proposal again by the next deadline. This remarkably high success rate is not because ICDP funding is easy to achieve but because science teams develop drilling proposals very carefully and stepwise after long-established research in a field or region; accordingly, a long history of funded research has been conducted. The usual pathway of proposals and reviews to ICDP is usually a three-step process with a pre- and a Workshop Proposal followed by a Full Proposal (Fig. 2.1).

**Resubmission of declined proposals**

First submissions of Workshop and Full Proposals to ICDP are often not successful. However, it is noteworthy that even the most prominent drilling projects have usually developed proposals over several years. Therefore, a proposal rejection can be regarded as a great chance to improve an outstanding idea, to resubmit an advanced proposal, and to make it acceptable for review boards in ICDP and for other agencies if no fundamental review criticism excludes resubmission.

Nevertheless, proponents should consider the assessments of the review panels and the comments from ICDP and others seriously. Each resubmission must include a cover letter or attachment explaining in detail how ICDP panel recommendations have been addressed in the resubmission. OSG will be available for additional information and direction.

**Main reasons to fail**

Most proposals to ICDP are accepted after revisions or addenda submission. Only very few proposals are rejected ultimately by ICDP because most projects are developed through side survey or similar studies which have been funded after a rigorous peer review as part of developing the funding base. In this way a certain type of success filter is already installed before ICDP comes into play. Reasons for rejections over the past ten years include:

- The proposal does not comply with ICDP criteria such as convincing management and engineering plans and budget
- The application does not provide a novel idea, has not the best site in the world, has no focus on a clear scientific objective or is not well written for international reviewers
- No sufficient pre-site survey exists or proof that key methods will work
- SAG and EC recommendations have been neglected in follow-up proposals
- The proposal does not generate enough scientific impact through PI group - often coupled with missing international participation
- Missing non-ICDP funding, lack of other support or competitors with similar projects
- Disagreements within the science team
- Missing coordination with other programs such as IODP; insufficient multidisciplinary direction
- Insufficient patience and persistence for the timely preparation and lobbying necessary for costly international projects

**Guidelines for proposals**

Full instructions for ICDP proponents can be found on the ICDP website. The published guidelines for ICDP proposals are updated regularly and should be followed. This includes: essential elements must be clearly outlined, page limitations followed, references correct and pages and figures numbered. Abbreviations should be avoided or defined at first time used. Apply a spell checker tool while a native English speaker should make language corrections as required. A final very careful editing and proofread is needed before submission.

Relevant 'negative' information such as previous proposal rejections should be addressed. Transparency is better than leaving reviewers with a negative impression.

**Requirements for Full Proposals**

An international group of proponents who has previously carried out an ICDP-funded drilling workshop may submit a Full Proposal. PIs who can demonstrate that they have held comprehensive, international and open scientific and technical planning meetings without holding an official ICDP workshop may submit a Full Proposal. The lead PIs of a proposal must be based in ICDP member countries. All formal requirements as outlined in the guidelines on the ICDP webpage must be followed thoroughly.

**Evaluation**

The Science Advisory Group (SAG) meets to review all proposals in spring each year. SAG reviews proposals and assigns priorities based on the criteria listed below:

- Quality of Science. Does the project address fundamental scientific issues of global significance, rather than just local problems? Is it international in scope and is the best drilling target worldwide being selected to address these scientific issues?
- Need for Drilling. Is drilling necessary to achieve the stated scientific objectives, or can they be achieved with surface-based studies at lesser expense?
- Qualifications of Proponents. Is the experience and productivity of the PIs plus the breadth and international diversity of the science team/workshop attendees sufficient?
- Societal Relevance. Is the project relevant to societal needs, such as energy, mineral and water resources, environmental and climate change, geologic hazards, etc.?

- Budget. Is the budget carefully prepared and reasonably describes the scope of the workshop or drilling project?
- Responsiveness. Where appropriate, have previous SAG/ICDP recommend-dations considered in the present proposal?
- Management. Does the proposal include a well-structured and feasible project, data and sample management plan?

As shown in Fig. 2.1, SAG forwards the proposal ranking and written reviews to the Executive Committee (EC) and Assembly of Governors (AOG) for authorization as an ICDP project, modification of request, or rejection. The EC and AOG meet back to back a few weeks after the SAG meeting. Following the panel reviews, PIs will receive the SAG review and a written summary from the EC and AOG instructing them of any requirements, conditions, or suggestions. The reviews and decisions will be made available to the PIs a few weeks after the panels decided.

**Land to Sea Drilling: Joint projects with the International Ocean Discovery Program, IODP**

The scientific ocean and land drilling communities have built two of the most successful and long-lasting international collaborations in Earth sciences. Despite targeting two distinct geographical domains on Earth, scientific ocean and continental drilling are strongly aligned due to the existence of the ocean-land transition zone, the fact, that geological units and questions may not be restricted to either of the geographical domains and in that their scientific objectives may only be sustained by innovative drilling strategies. Future scientific ocean and land drilling will emphasize transects from the ocean basins onto the continents, in research areas near and along coastlines, thus, enabling innovative collaborative drilling campaigns from land to sea.

Land-2-Sea (L2S) Proposals are for projects that can be jointly implemented by IODP and ICDP. Both programs focus on various challenging themes of global geoscientific and socio-economic relevance, including (1) geodynamic processes; (2) geo-hazards; (3) geo-resources; and (4) environmental change.

Land-2-Sea Proposals are those for which full achievement of the scientific objectives requires scientific drilling at both, onshore and offshore sites, or at shallow marine sites. IODP and ICDP have recently revised the proposal submission procedures for L2S Proposals. There is now a common proposal submission process at each proposal stage and a joint review process by IODP and ICDP with a clear schedule and set of guidelines for proponents. This will reduce the workload and simplify the process for L2S proposals, improve the efficiency and speed of the review process and hopefully encourage more scientists to submit such proposals. All proposed L2S projects will need to submit a Preliminary Proposal, a Workshop Proposal, and a Full Proposal. A workshop is required due to the complexity of such projects.

Proponents (Principal Investigators in ICDP and Co-Investigators in IODP) should prepare a single L2S Proposal at each stage combining the IODP and ICDP elements. Preliminary Proposals and Workshop Proposals should be submitted to ICDP and Full Proposals should be submitted to IODP via the IODP Proposal Database submission system. The IODP and ICDP programs will share all L2S proposal documents between them and arrange for joint review and response. To summarize, L2S Proposal submission requires a Preliminary Proposal, followed by a Workshop Proposal, and finally a Full Proposal. Details of the proposal submission can deviate somewhat from the submission procedure for other IODP proposals; therefore, proponents should pay close attention to requirements, deadlines and where to submit to at each stage. To the largest extent possible, review procedures of both programs are preserved. The joint implementation of a L2S Proposal will be resolved between the IODP Facility Boards and ICDP's EC and AOG, on a case-by-case basis. An overview of the criteria used for evaluation of proposals is provided at the following sites:

ICDP:

- https://www.icdp-online.org/proposals/proposal-review-criteria/

IODP:

- http://www.iodp.org/program-organization/science-evaluation-panel;
- http://www.iodp.org/proposals/about-proposals;
- http://www.iodp.org/top-resources/program-documents/policies-and-guidelines

For all types of proposals to ICDP applicants should adhere to the Writing Guidelines on the ICDP website and the various chapters within the Primer. These documents are available for download on the ICDP website and are regularly updated. Perspective proponents should approach the OSG team for questions and advise on proposal preparation. Members of the OSG are also available to assist applicants during the site-specific workshop. In addition, OSG members will help to develop operational support measures, such as instruments, down-hole logging, management, training, and others for Full Proposals.

## 2.4 Third party funding acquisition

One of the key principles of ICDP is the broad distribution of the financial burden of drilling. That means ICDP covers only parts of the operational funding for a drilling project and proponents have the duty to acquire matching funds from other sources. These are usually science funding organizations such as national research foundations, charitable societies, or industry project partners.

The acquisition of matching drilling funds and science support funds is frequently acquired from organizations of the country hosting the drilling project or national agencies of the leading PIs, Co-PIs, and Science Team members. The protracted, stepwise development of proposals in ICDP in conjunction with scientific in-depth reviews builds the foundation for a convincing proposal outline and text that can be utilized by the proponents to apply for matching funds after adaption according to funding principles of the

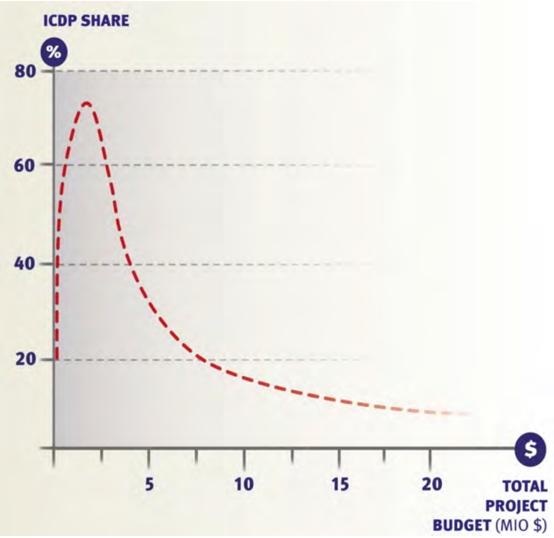


*Fig. 2.6 ICDP funding share vs. total project budget over 57 past ICDP drilling projects*

In the past a broad variety of funding organizations have been involved in ICDP projects as co-funders or main sponsor of projects and related research. Backed by this experience the ICDP OSG is capable to provide support in third-party acquisition for proponents. Once a project grant is approved by ICDP and thereby a base of funding established, PIs have improved chances to acquire third-party co-funding from non-ICDP sources. The amount of ICDP co-funding is highly variable (5 to 70% ICDP share) and depends on e.g., total costs and international breadth. Figure 2.6 provides a summary of the mean cost distribution in ICDP projects.

After successful application, the acquired funds can be used by the PIs to cover project expenses through their home institute. However, it is also possible that ICDP pools third-party funds in a separate ICDP account as needed; for example, if the PI's home institute requires that funds need to be spent by a certain time.

## 2.5 Program policies and project deliverables

An ICDP accepted and fully funded proposal is becoming a project and receives the branding 'ICDP Project'. However, the financial advantage is an obligation for the participating scientists to follow a number of duties.

Preparing a Full Proposal is already the start of project planning but after acceptance by ICDP the planning for the implementation of drilling operations and of related science needs to be fine-tuned. Funding for related science is usually well established in academia while the large funds needed for drilling operations often require unprecedented additional managerial, legal and budgetary efforts. Once ICDP has approved co-funding, the first threshold to tap funds will be the establishment of an ICDP Funding Agreement. This agreement defines the rights and duties of all project partners during the course of the project and regulates how ICDP's financial contribution is directed to cover parts of the operational costs, while scientific off-site work has to be covered through other sources.

Each agreement will be adapted to the specific project requirements while maintaining the critical issues ICDP compels for each of its projects. Cooperating partners of this agreement are the OSG and the project's PIs who sign the agreement on behalf of the Science Team of the project. A template for a Funding Agreement is available on the ICDP website.

OSG initiates funding of projects after approval by the ICDP boards and after the establishment of the funding agreement. In addition to the aforementioned issues it regulates how ICDP's financial contribution is directed to cover parts of the project's operational and other costs that are directly related to the campaign.

For each project ICDP administers all project funds at a specific project account at GFZ. There are two principle pathways to arrange the cash flow to a project:

- PIs forward invoices on operational costs to ICDP but check and approve the invoice beforehand. ICDP will then wire transfer payment of the invoices to the contractor from the ICDP bank account in Germany.
- One of the PIs establishes a project account at his or her institute, the office of sponsored programs, or alike, and issues calls for funds to ICDP along major project steps, milestones, etc.

**The Science Team**

An ICDP project is conducted by a Science Team consisting of a group of scientists and engineers that have been formed with the help of an ICDP workshop. An ICDP project is guided by max. 4 Principal Investigators (PIs) and max. 10 Co-PIs who usually develop the proposal and plan the project. The Science Team may be divided into groups of different scientific fields led by group leaders. Further leading roles are Chief Geologists/Scientists and OSG Staff Scientists. Chief Geologists lead the onsite science team and define, e.g., principles of sample handling, description and initial measurements. Jointly with the data and sample managers of the project the OSG Staff Scientist supports the science team before, during and after the drilling, supervises on-site and at the core repository the processes and supports the organization of sampling parties. Preferentially, he or she also acts as Data and Sample Manager and acts as the link between the project and ICDP. Other individuals involved, such as technicians, voluntary or temporary project-aids and subcontractors are usually not part of the Science Team. The Science Team members have a number of rights and duties on-site, at the labs, at the repositories or at affiliated institutes (see below). These can be independent from their actual participation. The PIs jointly decide who is a member of the Science Team.

The policies of the project should already be discussed and confirmed during the proposal development phase. Each Science Team member should commit to these rules and guidelines before the planned start of the operational work. The main topics for the PIs to decide before drilling include:

- Moratorium periods and milestones along the timeline
- Science Team – Selection of participating scientists, responsibilities, duties and privileges
- Data acquisition and sharing
- Scheduling and distribution of reports
- Sampling strategy and sample distribution
- Publication guidelines along the timeline
- Public outreach issues and internal confidentiality agreements

**Communication**

Communication is a central issue for any project. In most cases, the PIs, the OSG, the institutes of the PIs, as well as the drilling contractor are acting at separate locations at different times. It is therefore of paramount importance that a well-working communicatiobetween the project partners is established (see paragraph Timeline below). This is usually done in the funding agreement that defines all reporting issues. It is in addition noteworthy that a clear communication strategy for the Science Team needs to be implemented and maintained by the PIs and their mana ers in charge on site. The OSG can provide best practice examples how to link the different groups, needs, and interests.

**Timeline**

A drilling project is a long-term task that starts with an idea, pre-site surveys, proposal writing, planning, fieldwork, and sampling. It further extends throughout not only the drilling phase but also throughout the entire scientific evaluation phase and publication period that usually covers several years. Therefore, it deserves a high-level of attention from both, the project management and the entire Science Team. In a typical timeline of the operational phase a kick-off meeting serves to assemble the onsite crew of scientists and contractors, discuss milestones, HSE (health, safety, environment), as well as policies, rights and duties.

Data and sample management are essential parts of a successful drilling project and require thorough data and sample management workflows, plans and controlling. Without this management, a drilling project cannot be sustainable. Thus, a related training course offered by OSG is mandatory and should be envisaged within a six-month period prior to starting the drilling operations (Fig. 2.8; Chapters 4.4 and 4.5). Generally, the busiest part of the operational phase starts with rigging up and ends with the completion of the initial reports. During the drilling phase, the initial project data is collected using ICDP's mobile Drilling Information System (mDIS). This includes the multitude of drilling parameters, the intrinsic details of the drilling operations, the recovery of the material extracted from the hole, its sampling, core description, basic scanning and logging data, documentation, down hole logging data, and so forth. However, in many cases not all of these tasks can be executed and performed on-site due to harsh conditions or poor infrastructure. Consequently, the expedition is then divided into two phases: the drilling operation and the lab work usually starting with a thorough core description and a consequent sampling party. The lab work often takes place with a significant lag time due to the transfer of all the sample material from the sites to the target lab/repository (Fig. 2.8). At the time of the sampling party the basic data set collected within the mDIS needs to be available to the complete Science Team (see Chapter 4.4 for details). The Operational Data Sets and the related metadata are the essential parts of the operational report that ICDP requires to be made available. The projects Data and Sample Manager serves it a key position to fulfil this requirement.

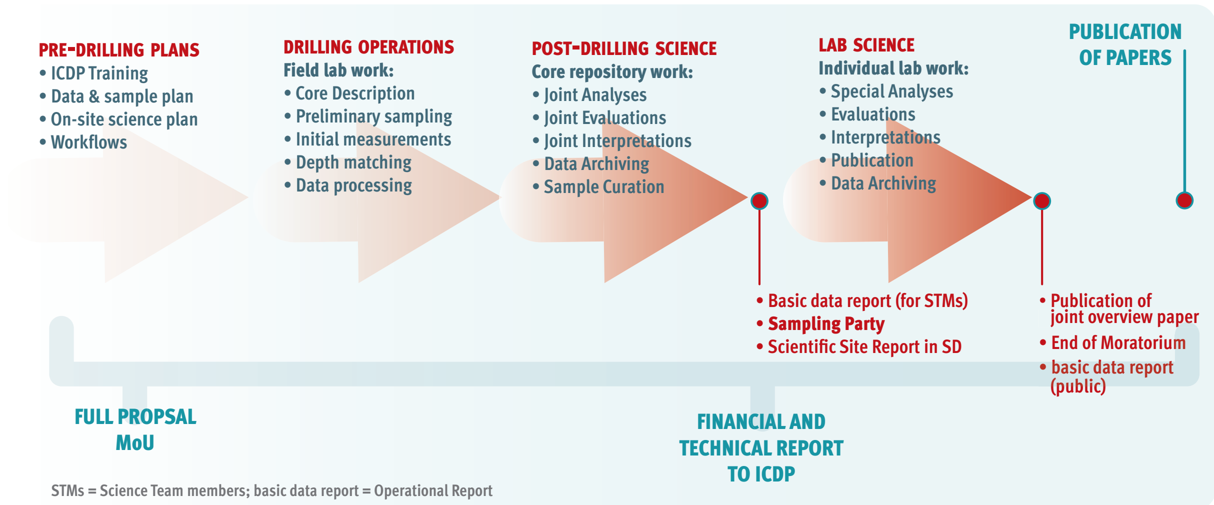


*Fig. 2.8: Typical timeline of a drilling project*

**Policies**

Through the funding agreement, ICDP requires a number of deliverables. In addition, the Science Team of a drilling project agrees upon some key rules, rights, and duties for all parties involved. Some of the main cornerstones in ICDP are listed in the following paragraphs.

The PIs and Co-PIs agree on Science Team members and Moratoria and their duration. Two main Moratorium Periods are usually applied (Figure. 2.8):

- The Operational Moratorium is distinct by the course of mobilization, drilling, demobilization, and the subsequent lab work. It should end with the first Sampling Party no later than six months after the beginning of the lab work.

- The Science Moratorium starts with the first Sampling Party and should usually not extend beyond two years. With the end of the Science Moratorium all data and sample material become available for open access under certain Creative Commons (CC) licenses (CC-BY or CC-BY-SA) to be defined by the PIs and ICDP.

**Data and Sample Rights and Duties**

- Each Science Team member can use all internal project data and all sample material for his/her own investigations within the context of the project
- Each Science Team member gets a personal login (username, password) to access the internal project pages of the ICDP Web-site
- A basic set of data (Operational Data Set) is required by ICDP to ensure long-term availability of scientific and technical data for future projects
- ICDP webpage login information has to be kept confidential
- Science Team members are neither allowed to use internal project data nor sample material for other projects or purposes during the mora-torium
- Science Team members agree to share their data and sample material, results and publications within this team
- Science Team members are obliged to follow rules of best scientific practice and cite data, information and samples as utilized

**Data Access**

During a project three main areas of access should be discerned:

- Internal access - restricted to the PIs on behalf of the Science Team, ICDP, and the drilling contractor.
- Science team access - restricted to the PIs and the Science Team until the Moratorium ends.
- Open access after the scientific moratorium project data and information is available for everyone under open access (Creative Commons (CC)) licenses.

**Reports and Due Dates**

Reporting duties are separated in this paragraph according to the access and availability. During operations the following reports are needed:

- Daily Drilling Reports from the drilling contractor to PIs and OSG (Internal)
- Weekly Status Reports from the drilling contractor to PIs and OSG (Internal)
- Daily Data Updates from the on-site science crew to the PIs, OSG, and the rest of the Science Team (Moratorium)
- Open: Daily Messages from the PIs to the OSG outreach team

After demobilization the following reports are due:

- Science Report that includes drilling and site report to be written by the PIs and to be published in the Scientific Drilling journal within 6 months after the operational phase
- Collection of the digital Operational Report including the Operational Data Set including related metadata; made available to the Science Team through the ICDP project web site and published after the Moratorium
- The open access publication of the Operational Report and Explanatory Remarks on a data repository linked with the ICDP project web site (with DOI) or via the ICDP web site only (without DOI) is published after the Moratorium
- Financial Report: A brief summary of project funds, budget and costs for all income and expenses. As a funding agency supported by tax payers money from more than 20 countries around the globe, ICDP has to report in detail to its stake holders and needs therefor these data.

Guidelines for all reporting duties are

available on the ICDP webpage.

**Publications**

All publications including contributions to conferences (abstracts, posters) by the whole Science Team and PIs shall be reported to the OSG; most co-funding agencies will require the same reporting of publications based on their co-funding to a drilling project. Copies or citations should be sent to OSG and other funding agencies once a paper is accepted and pre-prints or prints are available in order to allow recording and long-term availability of project references via the ICDP project web sites. This rule does not end with the Moratorium period.

**Acknowledgement of Support**

The Science Team and all cooperating scientists are obligated to acknowledge ICDP's support and help of co-funding agencies on any publication of any material, whether copyrighted or not, based on, or developed under this international project. The title and/or the keyword listed in publications should include the items 'ICDP' and the project acronym. The ICDP logo including text marker 'International Continental Scientific Drilling Program' should be visibly placed on posters or similar graphical material such as flyers, brochures, as well on CDs, DVDs, videos, etc. The ICDP logo is available for download on the ICDP webpage.

*Ulrich Harms*, Ronald Conze§, Katja Heeschen*, Carola Kögler*, Cindy Kunkel* and Thomas Wiersberg**

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**CHAPTER 3**

# Project Planning

**Ulrich Harms* and Santiago Aldaz***

Continental scientific drilling projects are complex undertakings bringing together scientists, drilling engineers and service companies, as well as funding agencies and other stakeholders. These parties have different professional backgrounds and often speak their own languages. Most Earth scientists are neither familiar with drilling engineering nor with large project controlling and budget management tasks. Drilling contractors in turn are generally used to drilling commercial projects with predefined targets rather than scientific paths with very special demands. Therefore, all parties involved must be kept together through very clear and regular communication pathways and a pre-defined rights and responsibilities structure. This is a key prerequisite for the success of any drilling project. Accordingly, proper project management is a crucial instrument in drilling.

Project management assists to initiate, plan, and execute scientific drilling. It allows for monitoring, controlling and finalizing a project by utilizing the main control aspects including time, budget, quality and scope. These factors allow to govern the progress and supervise the budget at all times during the course of a project and to define the achievements at its conclusion.

The Chapters 3.1 to 3.8 below provide first insight in the key elements of project management in scientific drilling. However, proper management of a pricy and extended scientific drilling project cannot be performed without experience and training. The Operational Support Group of ICDP, OSG, will provide all necessary support for project managers and PIs to initiate the project management. However, due to limited manpower and lack of knowledge on national regulations and language the OSG can, in most cases, not serve in ICDP project management. Therefore, ICDPs recommendation for drilling projects is to include experienced managers or hire professionals. This may cost extra money but will help to direct a mission to achieve the key goals without expanding the budget or being forced to descope operational objectives.

Several of the recommendations and figures used in these chapters are based on the PMBOK Guide (Project Management Body of Knowledge) issued by the American Project Management Institute, one of the globally leading institutions in project management.

OSG will help scientists at any project phase to manage and direct their project in a most productive and suitable way. Proponents and project scientists should at no time hesitate to contact OSG for help with project management.

CHAPTER 3.1

# Introduction to Project Preparation in ICDP

**Santiago Aldaz* and Ulrich Harms[&]**

This chapter offers a guideline through the project management structure for scientific drilling. It is based on general concepts and definitions from the PMBOK® (Project Management Body of Knowledge) and ISO Standard Guidelines. Best practice is to already integrate this scheme in full proposals to ICDP. Scientific drilling projects using a professional project management system from early on have usually achieved project goals within the planned time and budget limits.


*Fig. 3.1.1 Project Management Plan with detailed control factors known as 'Knowledge Areas'*

**Project Management Principles**

Actual project management systems necessary to establish a project management plan are primarily composed of the ten main knowledge management areas depicted in Fig. 3.1.1 and the five standard phases of project structuring depicted in Fig. 3.1.2: Initiation, Planning, Execution, Monitoring & Controlling, and Closeout. A project management plan should be applied during all five standard phases of a scientific drilling project. This means none of the project management standard phases and knowledge areas should be managed independently but as a dynamically integrated system as illustrated in Fig. 3.1.3. Project management systems are structures containing inputs, tools and methodology, and outputs following a chronological order.

A project management plan should be written before any action is taken for the purpose to:

- provide a clear picture of the project management organization, processes and guidelines for a scientific drilling project
- be an evolving and regularly updated document allowing to keep track of the development of a project
- keep all project stakeholders, including the project sponsor, senior leadership, and the project team informed about the progress and necessary changes of plans

A scientific drilling project is a challenging undertaking made by different teams and individuals with different backgrounds.

They deploy commercial as well as scientific drilling, logging, testing and evaluation technology. Therefore, the Principal Investigators (PIs) should elaborate from the start on – usually a proposal to ICDP – an ordered project management system that combines the main areas of knowledge project management with the five standard processes (or phases) of project management. The lack of a proper project management plan can lead to mistakes in project feasibility analysis, wrong time line estimates and underestimated budgeting calculations, lack of a quality management plan, a poor risk management plan and an inefficient procurement management plan with wrong deliverables or major project failure.

In this chapter, a description and explanation of the knowledge project management and phases is provided to support the PIs with a general guide of steps and recommendations to consider during the elaboration of workshops and full proposals.

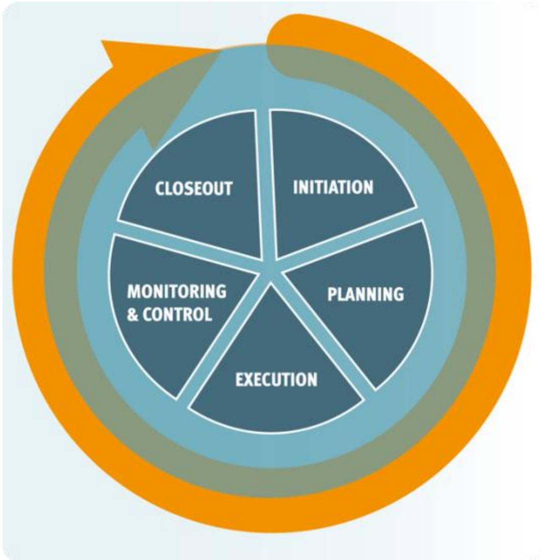


*Fig. 3.1.2 The circle of project management phases*


*Fig. 3.1.3: The seven project management knowledge areas encircling all five phases of a project*

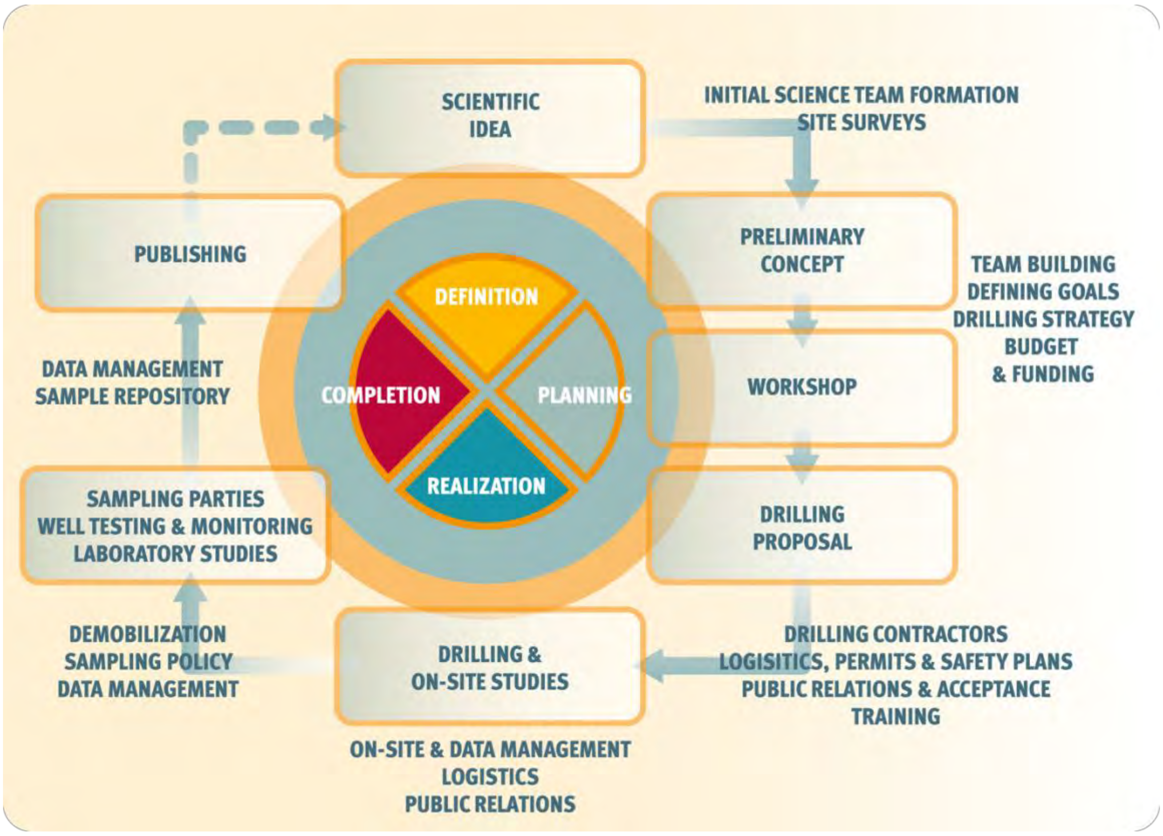

*Fig.: 3.1.4: Management roadmap of a scientific drilling project from scientific objectives point of view*

**Program management phases**

Scientific drilling can be subdivided from a managerial point of view in a sequence of five phases as shown in Fig 3.1.4:

- **Initiation**: In ICDP this is the phase of a preparation of a pre-proposal or, in some cases, a workshop proposal in which the core of a science team sets up an idea and submits this to ICDP. It defines key scientific questions and testable hypotheses and includes a brief evaluation of existing data and surveys around potential drill sites.
- **Planning:** The concrete planning process starts with an ICDP-funded workshop that serves to define the project objectives in detail, to implement a drilling strategy to achieve these goals and discuss funding options while building an assertive team, evaluation of project feasibility and defining policies are other critical workshop issues. In addition, the workshop paves the way for the preparation and submission of a full proposal and to funding acquisition from ICDP and other sponsors.
- **Execution:** The realization or execution phase includes all operations on the drillsite embracing technical actions such as drilling, but also scientific-technical duties such as downhole logging and later the scientific measurements on samples taken and acquisition of the data gained. Once drilling has ended, a phase of scientific testing and monitoring in the well follows in many cases. The sampling on cores and analyses in the different labs collaborating in science is also part of this phase. It is also necessary to perform well completion and abandonment and to demobilize the drilling equipment.
- **Monitoring and controlling:** This is the dynamic follow-up of real time project developments. This serves to identify deviations from the original time plan in order to execute changes, corrective actions and improvements that will

steer the project back on the planned tracks to achieve preestablished project goals.
- **Closeout:** The final closeout phase means publishing of results of all investigations performed by science team members and the handover of the fully rehabilitated drillsite to the owner.

The crucial steps for scientists initiating a drilling program starts when drilling funding is at hand since the concrete drilling planning, the permitting and all logistics and related schedules must be organized. In order to cope with this task a management plan as outlined above is the best guideline for all actions. If later drilling engineering planning is set up e.g., with support from external project consultors and permitting is achieved, a drilling operator and services companies must be selected and hired. Again, the management plan will serve to keep track of actions required. This includes e.g., drill site civil construction work, drilling, coring, and well logging equipment selection, on-site logistics and continuous supplies, sample and data management and also an appropriate training of future on-site staff.

Furthermore, an oversight panel can be implemented to provide advice on operations, work safety and to make recommendations during all different kinds of problems. During project execution it is also advised that field PIs stay at the operations site. If PIs cannot be permanently present at the rig site during drilling operations, it is recommended to delegate an on-site chief scientist who will coordinate all activities concerning drilling parameters, core recovery, handling, in-situ analysis, well logging activities and shipping of samples with the crews at the rig site. Sample and data storage and their distribution to the science team are sensitive tasks to accomplish the project.

An additional science advisory board can support Principal Investigators (PIs) in all major decisions that may jeopardize the scientific goals. Scientific drilling projects will attract a great deal of attention and maybe trigger concerns by local communities, authorities and politics. Therefore, carefully planned outreach activities are crucial for a successful project realization.

CHAPTER 3.2

# Project Integration Management

**Santiago Aldaz***

Project integration management is a dynamic process to update a management system in any phase and at any time of the project. The aim of integrated management is to develop a collaborative pathway through the project knowledge areas and project phases to accomplish project goals and requirements.

Very often at the beginning of the scientific project a PI may ask him- or herself: how do I start my project following a structured process to integrate all information together? To answer this question the PI can follow the seven project processes of project integration management that are linked to the five standard project management phases as illustrated in Fig. 3.2.1.


*Fig. 3.2.1: Project Integration Management Process*

In the initiating phase that involves the project charter knowledge the PI together with the project stakeholders can authorize the project conception, settling the definition of the project scope, goals and objectives with corresponding required human and material resources. The project charter can assist you in defining a high profile of the complete project management plan to reach specific goals and expected deliverables including personnel, responsibilities, tasks, required environmental permits, resources and infrastructure, budget and time deadlines to set the project on paper before moving forward to the planning phase and project execution phases correspondingly.

The ICDP workshops as described in Chapter 2 are key elements in the philosophy of the ICDP for approaching detailed planning of a scientific drilling (Fig. 3.2.2). Next to scientific planning and preparing a full proposal, the workshop serves to bring together science leaders with drilling professionals to assess engineering requirements and costs; in other words, it serves to start the project management in this Initiation Phase.

ICDP´s financial support for drilling is based on a comingled funding principle. This means that PIs are requested to acquire additional funding from sources others than ICDP. Therefore, it might be necessary to broaden the scientific goals to make a drilling project attractive for different funding agencies. The following issues are to be addressed by a scientific drilling workshop before any further preparation of a full proposal:

- Have the scientific goals been clearly identified?
- Is there agreement among the science team on what drill hole(s), samples and
- measurements are needed to achieve project goals?
- Is there a "critical mass" of committed and enthusiastic participants for the project to succeed?
- Have the PIs and engineers made an adequate assessment of the technology required to archive the project goals?
- Are project goals and the drilling strategy in balance with the funding concept?
- Have other potential funding sources been identified?
- Are additional site surveys or feasibility studies necessary?
- Have the next steps and timelines been discussed?

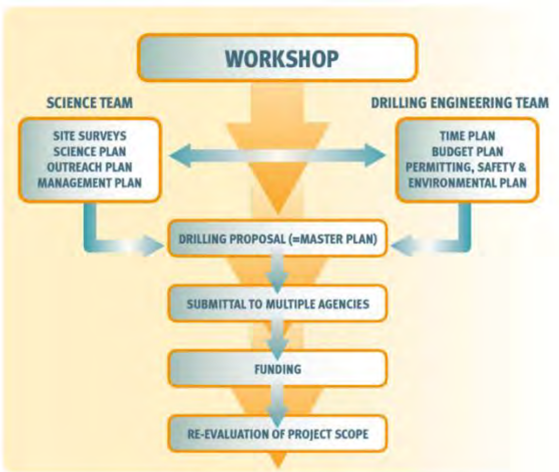


*Fig. 3.2.2: Flow chart of post-workshop key duties*

The outcome of a successful workshop will set the base for the full drilling proposal to be submitted to different funding agencies, including ICDP. One of the prerequisites for a successful drilling proposal to ICDP is a detailed project management concept as explained in this chapter.

An excellent base for the success of national and international scientific drilling projects has been the early establishment of a clear and ordered Project Charter. This is the definition of the mission of the project addressing issues such as:

- What are the goals of the project?
- What are the success measures?
- Why will the project be conducted?
- Who manages the project and what are their duties and rights?
- What are the project deliverables?

There are several other points to be included in the Project Charter like the benefits, restrictions, limitations, expected results, deliverables, organization policies, disadvantages and identification of main stakeholders and their expectations of the project results, among others.

Proponents of full drilling proposals to ICDP should bear in mind that the project management and proposal preparation need to go hand-in-hand. A full proposal needs to address the scientific justification jointly with the planning of the science but at the same time also the planning of the drilling operations. While the first is a key driver in the initiation phase, the latter can often only be fully detailed once all funding is at hand and concrete plans for time and budget, quality, risk, human resources and procurement management can be finalized.

As ICDP support is focused on drilling operations it is advised to prepare the drilling planning in a full proposal document following international enginee-ring, quality and operational standards from certification organizations (API, ISO, OHSAS, TÜV, IADC, etc). This will save time and effort for the upcoming quality and risk management process of the project. Since most scientists are not experts in drilling project management, PIs should consider external support to have professional guidance in project management from the conception to the execution. The costs for external management services should already be included in budget calculations for the proposal. ICDPs Operational Support Group can help to set up these tasks or to find professional managers.

All resulting information form the project integration management plan and can be organized into scheduled charts like waterfall Gantt charts to visualize the project future development, track milestones, adapt to changes, set up backing plans, etc. (Fig. 3.2.3). For full scientific proposal submissions, it is mandatory to include a scheduled project management plan and chart showing tasks, required resources and due dates for scientists, engineers, logistics personnel, laboratory personnel, outreach and media team, educational team and all resources and personnel involved in the 5 standard phases of project management process (Initiation, Planning, Execution, Controlling and Monitoring, Closing).

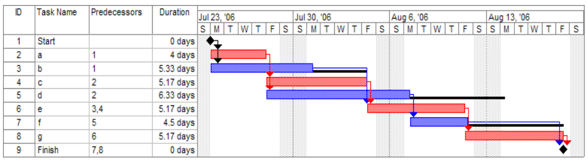


*Fig. 3.2.3: Gantt chart example to show tasks, duration, and timing (Source Wikipedia)*

Quality management and risk analysis management plans must be integrated in all project phases and must identify potential hazards that can injure personnel, damage natural resources and infrastructure or destroy machinery which can put the project out of track without reaching the goals within the limits of calculated time and budget. A more detailed explanation is featured in the following chapters 3.4 and 3.7.

The communication and interaction path with all personnel involved must flow smoothly and be organized in a way that the knowledge acquired during all project development phases is transmitted efficiently. This will ensure the effective completion of every process of the total project. PIs and project managers must be aware that these are not simple tasks and, at some point, will go through situations where the three main constraints scope, budget and time cannot be balanced without losing quality or leaving the planned schedule. Thus, the PI must be prepared and holds backup plans ready that were developed in the planning phase. They will assist him or her to perform controlled project management changes, to monitor the effect of such changes, and to keep the project under control.

In Chapter 4.2 the well planning management is laid out in detail. It should be noted that project managers must consider the advice of experienced personnel. In combination with an organized task assignments, it will substantially minimize or even eliminate so-called non-productive time caused by unplanned events and it will consequently minimize budget impacts and improve project results.

Finally, after integrating the four previous phases, a project transforms into the closing phase. From a scientific point of view, data quality is the most critical expected outcome of the project execution. Data generated during drilling operations include technical parameters or core recovery rate and core quality. In addition, downhole logging and on-site sample investigation data are critical outcomes. They can only be achieved through excellent project management organization and outstanding performance of the whole team involved. Finalizing a project within the planned budget and time frame will be reflected on data analyses and reporting as well as the further elaboration of deliverables and their societal impact.

CHAPTER 3.3

# Project Scope Management

**Santiago Aldaz***

The scope management knowledge focusses on defining the goals, resources, and requirements of the project in agreement with the project stakeholders. Once the involved partners such as stakeholders and PIs have agreed on a project funding and execution, the next step concentrates on defining the deliverables. Such a scope management usually consists of six steps as shown in Figure 3.3.1 with each step or process supporting the proper identification inputs, tools and techniques, and outputs to organize a project properly.

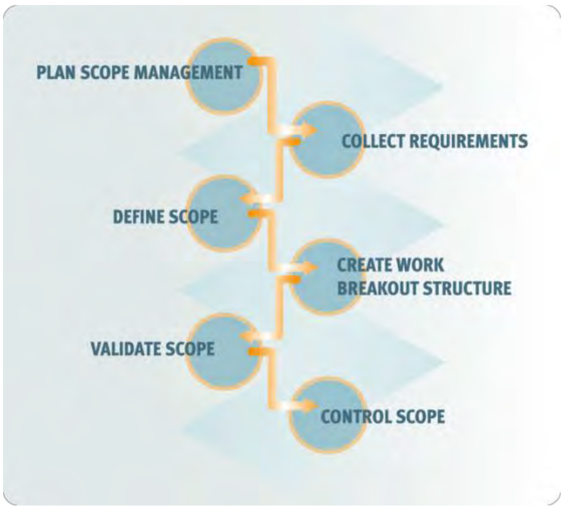


*Fig.: 3.3.1 Project Scope Management Process*

A project scope management plan will allow to point out:

- The scientific goals and objectives of the project within the key science themes of ICDP: Geodynamic Processes, Geohazards, Georesources, and Environmental change
- Requirements, conditions and deliverables, including personnel and their skills, companies or organizations policies, project management strategy and methods, local liability, environmental constraints, expected reports, papers, existing and new guidelines, improved standards and procedures.
- Identify limits and feasibility of the project such as regional liability and compliance, available technology and scientific knowledge, expected time to obtain results, overview of potential assets to procure, potential and committed stakeholders, alternative planning.
- Target specific work to do to improve expected results encompassing implementation of a quality and human resources planning management system, assigning task and responsibilities to appropriately skilled personal, identification of job necessities, setting up proper supply chain process from a procurement management system, following results continuously to reflect improvement in deliverables.
- Tolerance and acceptance conditions for project development through evaluating risks from the top view of the project; adding a risk management plan for the further development of the project structure; definition of project limits assuming, transferring and avoiding risks; considering personnel experience, borehole conditions, equipment availability, geography and

regional location, societal and security issues.

- Estimates on cost versus budget and identification of resources needed after identifying the required personnel, technology and equipment, timeline and deliverables that accomplish the stakeholders expectation; this will be complemented by an evaluation of costs in each part of the processes and an calculation of the required budget.
- Delineate human resources profiles and organization structure: assign tasks to appropriately skilled personnel, don't underestimate the complexity of the project and tasks. This assumption may lead to a total project failure.
- Recognize earlier hazards that can generate risks which lead the project to a failure state: delineate a quality management and risk management process for the whole project.
- Define time schedules, tasks, responsibilities to track, monitor and control the project: daily check and earlier identification of deviations from your original project integrated management system will help you to make organized changes and correct mistakes earlier. Keep in mind that in drilling and coring operations forecasting with controlled changes are key drivers to improve core quality, well logging and the resulting acquired data.

# Time and Budget Management

**Santiago Aldaz***

Time and budget are two dependant variables along the project management strategy. During drilling and coring operations, the best strategy to optimize resources is to drill faster without missing safety procedures, quality and engineering standards that have been pre-established in the integrated management system. Drilling operations consume most of the time and budget resources of a project. Therefore, they have to be detailed in advance with corresponding specific due dates and calculated costs along a chronological order. The drilling planning can be straightforward visualized and controlled using a Cost vs Depth graph as shown in Fig. 3.4.1.

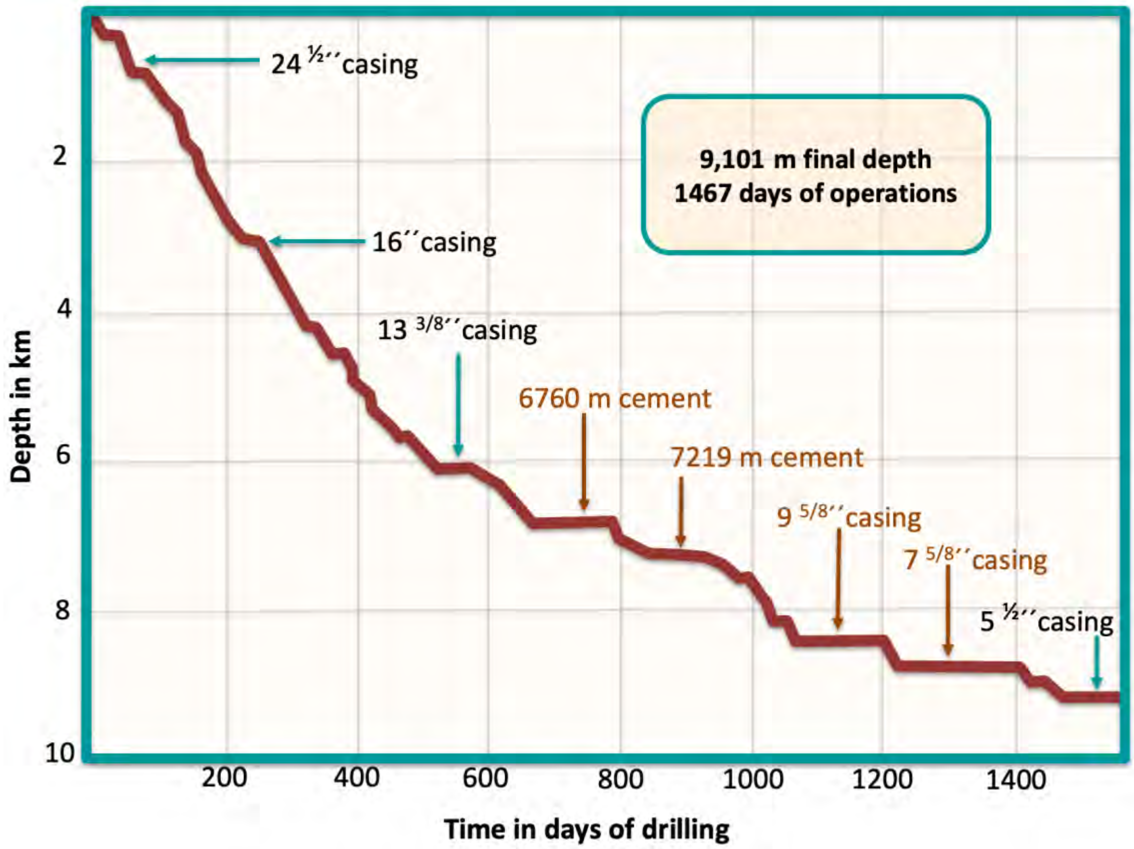


*Fig. 3.4.1 Depth versus duration of drilling for the KTB well in Germany. Note that duration and costs are directly correlated. Major delays marked with brown arrows caused major cost increases.*

The experience of the well engineering planner and operations supervisor will be fundamental for estimating the project drilling time, budget plan and the synchronized field operations. The PI and the planning team will set up a proper justified drilling time and budget plan which will be forwarded to drilling companies to request service quotes or to extend formal invitations to participate in bidding schedules. Assistance in this time-budget evaluation phase can also be requested from the ICDP Operational Support as part of ICDP support at no extra costs.

The OSG recommends to start planning a scientific drilling full proposal by arranging a detailed 'tasks to do list' by classifying due dates, priorities, resources, progress while the cost of each task is quantified individually. Information about all the estimated labour (man-months) by category (technicians; researchers; senior researchers), sub-contractor expenses, material & supplies, rental, financing and software cost must be included. All budget items have to be listed with all applicable taxes such as VAT for the relevant country where the expense will be incurred. It should be kept in mind that the more detailed a full-proposal is, the better the resulting budget calculations will be.

Full scientific drilling proposals forwarded to ICDP for funding have to be supported with a detailed estimated project time-budget plan outlining the pre-drilling preparation (drilling permits, location and infrastructure), the drilling operations schedules and the post-drilling phase (well completion, monitoring, plug and abandonment). After successful proposal evaluation and awarding by ICDP and other co-funding agencies, the PI will be asked to confirm or update time-budget details with the selected drilling or service companies. The PIs should then contact the ICDP Operational Support Group to analyse budget deviations and project feasibility. ICDP requires third party expenses over US$ 100,000 to be supported by three competitive quotations not older than 3 months. National or multi-source funding may be obliged to follow other regulations and require national or international public tendering for services and supplies over a given value.

During the project execution phase, a PI or the designated project manager must monitor and frequently compare the actual state of the project against the planned base line. In this way, any identified deviation from the baseline of the project can be corrected as early as possible and task and cost changes can still be positioned into the planning resources to mitigate negative consequences. Informed stakeholders will neither complain nor have doubts about the progress of the project if changes are made transparent through detailed and adjusted plans, especially if a quality management plan is executed in parallel.

Daily cost control during drilling operations is essential. In order to achieve this, daily drilling operations meetings will be needed. They serve to review daily activities and to agree upon operation forecasts with all teams and companies involved in the project execution. This enables project managers to recognise if the plan is getting off track, costs are soaring above the expected limit and activities are delayed. In this case it will be necessary to get back to original plans and consider backup plans that were analysed in the project risk matrix evaluation. Another key point to keep in mind is that in drilling operations proactivity and communication with experienced personnel are key factors to solve problems and achieve solutions before it is too late. Drilling and coring problems such as delays, increased budget, missing targets are notoriously known for worsening if issues are not detected on time and not corrected as soon as possible.

ICDP holds the PI or the nominated project manager responsible for cost controlling and financial accounting. A best practice is that PIs report the actual financial project status on a weekly basis to the ICDP-OSG including a look ahead for the next month. In the course of the project invoices and/or request for money advances will be forwarded by the PI or assigned project cost controller with supporting documentation to ICDP for payment. Deviations to the approved budget will have to be explained and technically justified in sufficient detail. Transfer of funds between the budget categories over a value of US$ 10,000 will require written approval from ICDP prior to the incurrence of the expenditure. Three months after the project ends a full financial report has to be produced and submitted to ICDP for financial review and/or auditing purposes. All bookkeeping documentation, receipts as well as money transfer bank reports have to be filed by the PI´s institution after project end for a period of 5 years. Fiscal regulations in some countries may even require a longer time period, and PIs have to ensure compliance with such regulations even after the completion of the project.

CHAPTER 3.5

# Quality Project Management

**Santiago Aldaz***

A proper quality management plan optimizes resources, creates commitment and responsibility among the team players and improves productivity while the scientific drilling project results fulfil all pre-established stakeholders and organization expectations. At the beginning of the planning phase a PI might ask: How is quality related to the target, time and the cost and budget to develop and improve my scientific project? One of the answers to this question would be that the earlier a cause effect is identified the lesser the impact on your time budget will be. Furthermore, it will be possible to develop a continuous improvement strategy and direct the control of the project back on track following the planned base line. This means developing a quality management plan that will allow maintaining conformance to pre-established requirements to fulfil the expectations of stakeholders in terms of policies, standards, guidelines, procedures, time, resources, and ultimately results.

The commitment, accountability, and leadership of the PI with the team determines the success of the quality management plan. The PI should develop proactivity skills to be able to lead and guide the project towards successful results that satisfy all stakeholders and allow reaching the scientific and operational project objectives.

Several scientific drilling projects were executed differently than the original plan. The problem of many drilling experiments in science is that they face increasing costs and cannot reach targets as planned due to unpredicted geological conditions at depth and technical failures during drilling. In order to support decision making in the critical phases of drilling an advisory board can be involved in all major decisions. Such a panel can help to find solutions, increase decision acceptance, and to acquire contingency funding, if necessary. However, for every decision on modification, careful consideration must be given to the overall project objectives, timeline, resources, and quality. No topic can be changed without affecting the others.


*Fig. 3.5.1: Project management tetrahedron showing interdependency of key factors (knowledge areas)*

ICDP experience in scientific drilling shows that it is almost impossible for PIs to find a perfect balance among the four key parameters time, targets, costs, and quality as presented in Fig. 3.5.1. The tetrahedron shows the interconnection and symbolizes that any change e.g., in costs will impact time, quality and target. For example, drilling and coring a well faster as planned (less time) may save time but can, at the same time, effect the core recovery rate or borehole stability (less quality) negatively.

A quality management plan as shown in Fig. 3.5.2 will minimize the effect of having unexpected cause-effect situations or unprogrammed changes in time, budget, quality and goals along the execution of your project. Quality management is a process that consists mainly of three subtopics:

- Quality Planning: definition of quality standards, policies and procedures, plus the identification of problems
- Quality Assurance: strictly following and executing the quality planning, identifying continuous improvement actions, optimization of resources and improve performance by avoiding non-added value activities. Evaluating the development and accomplishment of project objectives against the pre-established policies, standards, and processes.
- Quality Control: evaluation of project results through prevention vs. inspection plots, Pareto charts, cause and effect diagrams, check lists. Checking conformance of results, deliverables, reports against the stakeholder's expectations. Identifying cause effect pinch points, continuous improvement and good practices implementation.

From the conception of the scientific drilling pre-proposal, up to the execution of the project, the whole process should be supported by quality management until the project ends.

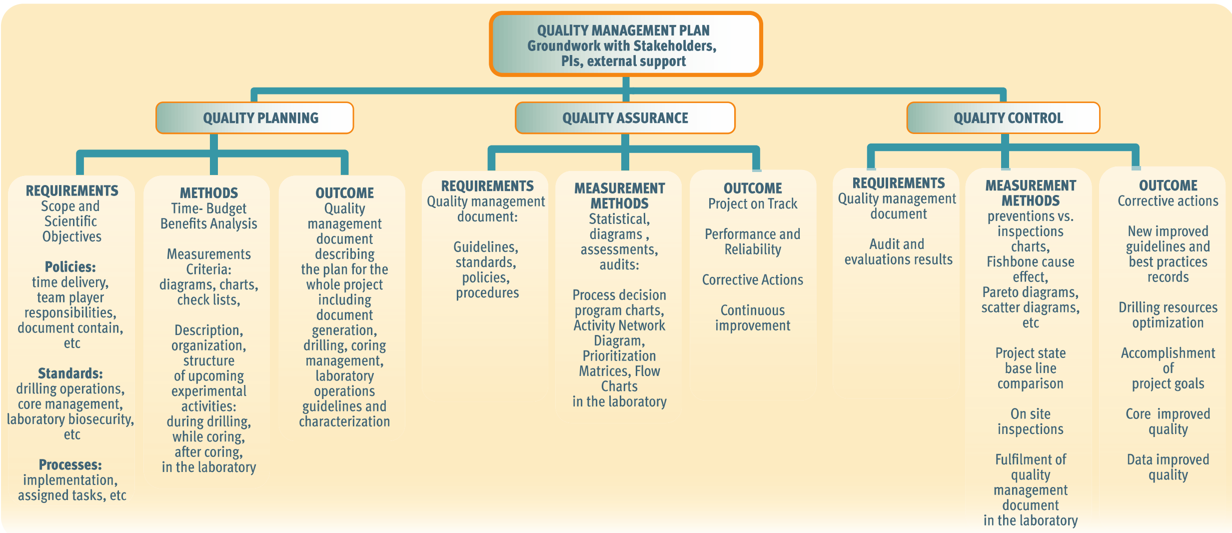


*Fig. 3.5.2: Quality Management Plan*

PIs without previous project management experience should seek external assistance from ICDP or consulting companies. In addition, the expenses for professional support should be added to the project budget at least as a rough estimation. Already in the proposal phase PIs will need to identify and, in some cases, establish new policies, standards, and processes that shall be accomplished during the full life cycle of the project. This includes the proposal document, (pre-)site survey, environmental permits, drilling permits, drilling operations, coring management, documentation and deliverables. Having prepared a time budget baseline together with an effective quality management plan will also facilitate the risk management process elaboration.

CHAPTER 3.6

# Human Resources and Communication

**Santiago Aldaz***

The concrete planning of scientific and technical operations as discussed above helps to define the needs in personnel and the organization of human resources for all project phases. For example, should a science plan for the operational phase include a concrete list with guidelines and instructions for sampling, logging and monitoring? Based on such a list, technical and personnel requirements can be estimated and time and costs calculated. In a similar way the drilling contractor will determine the staff needed such as tool pusher, roughnecks, and helpers in each shift during the drilling phase.

### Science Team

One of the top priorities is then to define the roles, responsibilities and duties of all people involved in planning and conducting the drilling project. This can be mapped out as an organization chart or management plan flow diagram that visualizes key tasks, related people in charge and main duties. An example of a scientific management diagram of a project is given in Fig. 3.6.1. Responsibilities of the on-site science team could include:

- Retrieval of drill-cores and rock cutting samples
- Inventory and documentation of samples
- Routine logging of samples according to specified on-site program
- Preparation of preliminary lithological log (litho-log)
- Transfer and deposition of samples in a safe long-term repository
- Compilation and preparation of interim and final reports

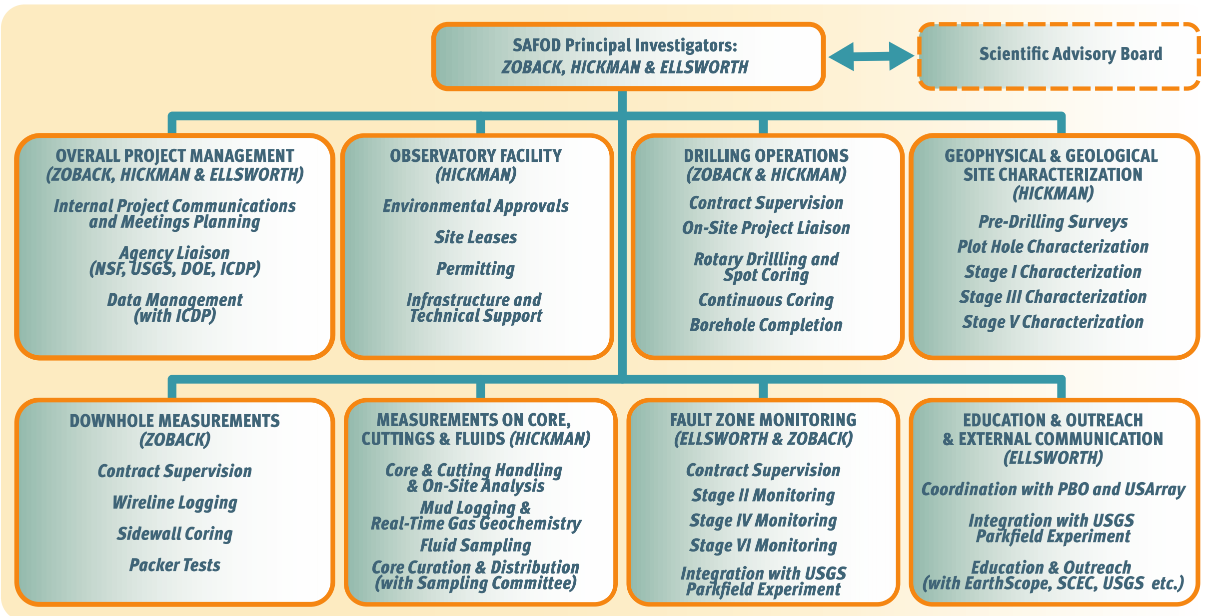


*Fig. 3.6.1: Management plan of the San Andreas Fault Zone scientific drilling project.*

In addition to the direct project responsibilities within the science team this graph also shows an external advisory board that provides advice on all major decisions. Such a board usually consists of external experts such as industry representatives, PIs and the program managers of major funding agencies.

**Company man**

While many of the tasks lined out in Figure 3.6.1 can be performed by experienced individuals from the science team, the planning of a well along with contracting and supervising a drilling company needs an experienced project manager with a strong background in drilling and completions engineering and operations. A full project proposal to ICDP must be submitted with a well planning section, that can be elaborated by a senior drilling consultant with a drilling engineering and operations background. This is usually an experienced drilling engineer field supervisor who can also perform the position of "company man" during drilling operations. He or she will report directly to the Principal Investigators or an assigned head of the on-site science team and will control all contractual actions and will be the link between the science team and the commercial drilling and related services. As a facilitator for communication between both, science and engineering, it will be the duty of the company man to follow the project development closely in the front line with fundamental understanding of the well operations, problems, restrictions and good practices.

**On-site management**

Especially during drilling operations, a close collaboration between the drilling crew led by the drilling supervisor or company man with the on-site science team is crucial. An example of interaction of a science team with the drilling action is given in Fig. 3.6.2. Such complex interaction can only be managed if best practice, continuous smooth communication, excellent collaboration, and constant knowledge transmission are established.

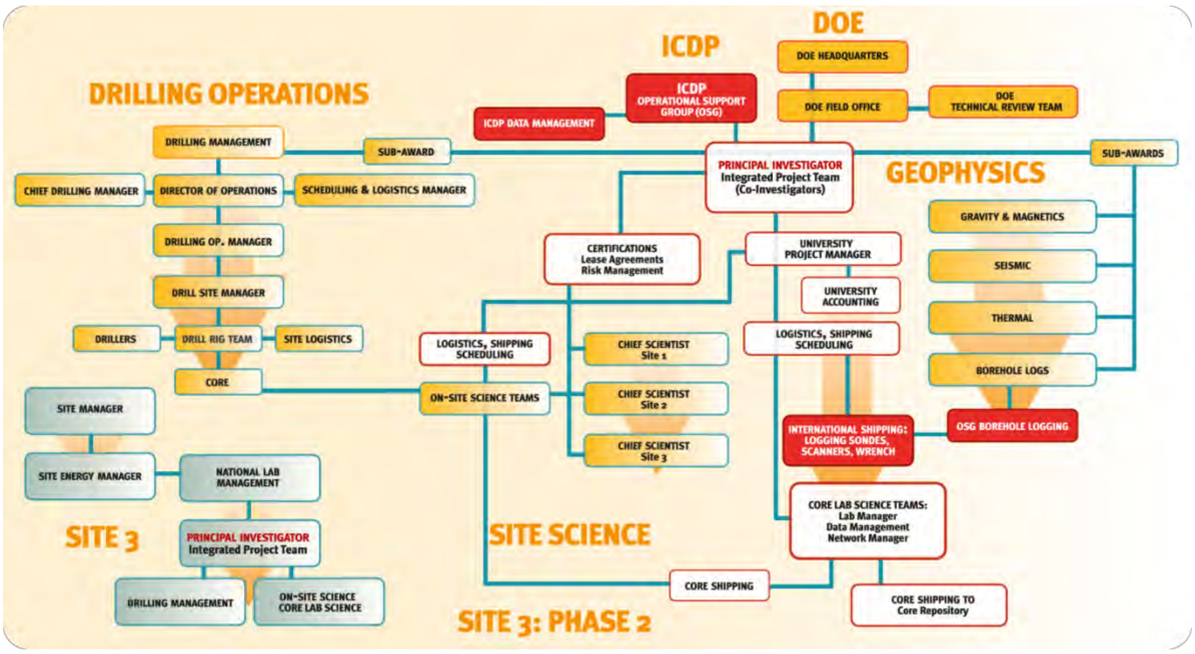

*Fig. 3.6.2: Example of a complex project management structure (ICDP Project Hotspot, Snake River Plain, Idaho, USA.*

It is important to define the appropriate number and skills of staff needed on location to assure a suitable and successful execution of a project. The rig crews working schedule defines the overall work. If – as usual – drillers work in two 24/7 shifts the science team that, for example, has the duty of describing core as it surfaces could work in coordination with the drillers. In this context the following considerations attain significance in deciding about the number of science staff required to perform jobs on site:

- How extensive is the scientific on-site program?
- How quickly is the information required to be available?
- How many activities are scheduled within the given timeframe?
- What is the duration of the drilling project and for which time is workforce needed?
- What are the specific regulations about regional labor laws?

**The on-site science teams**

The following job description serves only as a broad guideline; things may be different in each project and need to be adjusted to the specific scientific drilling project requirements – without compromising any pre-determined safety considerations and following preset time-budget, quality, risk management plans.

The chief scientist is overall and ultimately in charge of scientific work and coordinates all activities of the project concerning the recovery, handling, analyses and distribution of samples retrieved. He/she reports to the (other) PIs and keeps them updated on the day-to-day progress of the project. He advises contractors (if no company man or manager is acting on his/her behalf) and receives operational reports. Furthermore, this individual is responsible for organizing the field laboratory, sampling parties, budget and procurement and maintenance of equipment. Therefore, somebody who has a thorough understanding of the entire process of drilling and related issues should serve in this function. A detailed knowledge of the geological setting and expected lithology at the drill-site will be another key advantage.

The field geologists take over the recovered cores at the derrick and carry out all core handling, description and field investigations as agreed upon by the Science Team. They take care by following e.g., a core flow procedure as shown exemplary in Fig. 3.6.3. Such handling of the core and all other samples must be firmly implemented through a protocol established in the planning phase. A predetermined flowchart will be part of a quality management plan – primarily based on the "Safety-First" principle, and secondly on scientific objectives, as defined in the science plan. The core protocol can significantly vary from project to project – for example, the imaging could be conducted prior to boxing; certain microbiological studies require special handling of sample material, and depend on several factors such as logistics, priorities in the science goals, budget and overall costs, etc. If only cuttings are available, they should be washed, dried and analyzed. Data of any kind must be compiled in log sheets and a project-specific database (Chapters 5 and 8) to keep the litho-logs up-to-date.

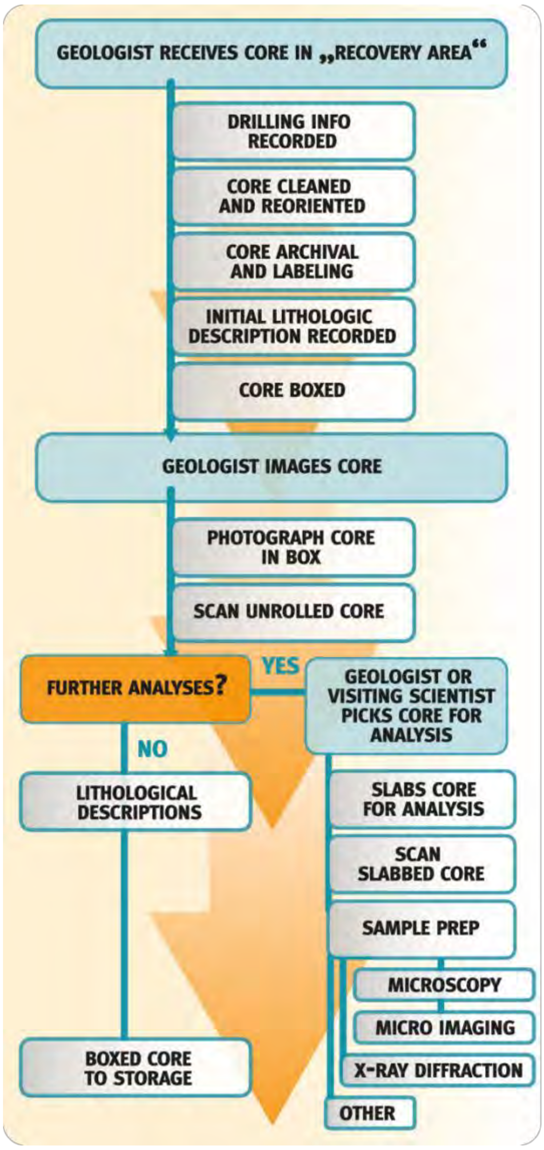


*Fig. 3.6.3: Core handling protocol*

The **data manager** has to configure and setup the mobile Drilling Information System, DIS (see: Chapter 5, "Data and Sample Management") prior to drilling, which will then allow data input simultaneously with the drilling operation. Installation and maintenance of internet connections at the drill site and providing all necessary computer-related assistance in report preparation are also part of the duties. Field technicians, scientists or volunteers prepare and label core-boxes and take the cores from the drilling rig to the field lab, where they wash and clean the cores, and label core pieces. They can also be employed to assist in sample documentation, e.g. with a camera or core scanner. For drilling projects where cores ought to be split into working and archive core halves, this field crew can help to cut the full cores. Experts in structural geology draw orientation lines and designated curators make inventory lists to assure a proper handling and logging of all core/sample material for future storage and/or sample material distribution around the world.

CHAPTER 3.7

# Risk Management

**Santiago Aldaz***

An objective view on any deep scientific drilling project reveals that it cannot be compared to scientific work at a university or research institute: academics and industrial contractors in complex inter-action, hard-hat-work, high costs, and a usually pretty unknown outcome are key features. Scientific drilling is therefore always risky but funding agencies providing the grants to drill require a safe and predictable outcome for their large investment. Accordingly, PIs are challenged to develop a detailed planning including professional risk management to achieve the operational objectives of scientific drilling projects in the best possible way.

Risk management is a process to identify, analyse, evaluate, and treat potential risks that can affect, threaten or cause damages to personnel, equipment and material resources of any project that will not allow you to reach your pre-set project goals. The process is illustrated in Figure 3.7.1 below. It comprises the following pillars of communication and consultation:

- **Scope:** points out the objectives and targets, needed resources and expected results obtained from the risk mitigation and management process
- **Risk assessment:** focuses on three key drivers including i) identification of hazards and causes, ii) analysis of potential risks and their probability of occurrence, and iii) evaluation of results of previous analysis against the targets set. These drivers are fundamental in classifying the risk severity and consequent damages and help to define its corresponding treatment.
- **Risk treatment:** defines if the risks associated with planned activities are acceptable or have to be rejected or the likelihood of their occurrence need to be minimized. This is fundamental for the development of drilling project contracts because with the understanding of assumed risks, project managers are capable of deciding if insurances need to be acquired or if risks are taken by the project.
- **Recording and reporting:** information generated through the three previously listed topics shall be communicated to the stakeholders and assigned project personnel. Corrective actions, upgrades or rescheduling must be pertinently communicated to them and executed neatly.

Project management is a dynamic process that needs to be adjusted at any stage or phase of the project development. Thus, it is necessary to establish a continuous monitoring and review method to keep an updated track of results and the effects of the risk management strategy.

The risk management guidelines in this chapter are based on the norm ISO standard 31000.

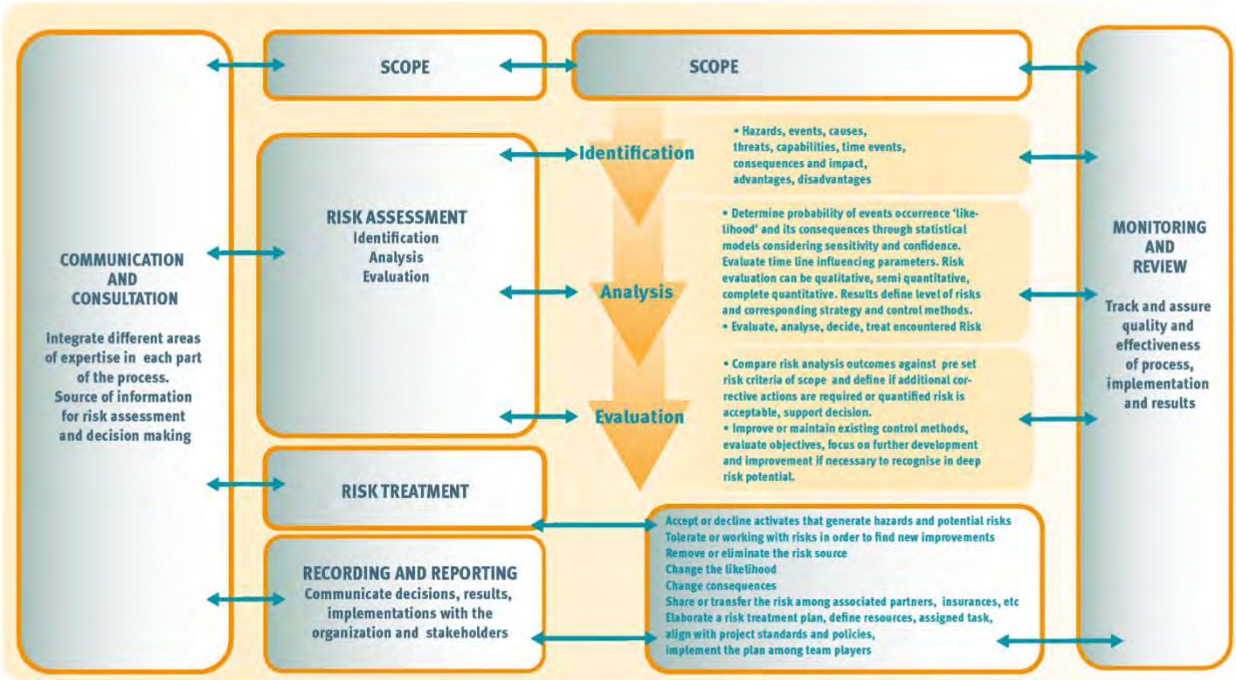


*Fig. 3.7.1: Integrated risk management process*

An easy and very common way to lay out risks and their mitigation is to show them in a matrix graph based on qualitative, semi-quantitative or quantitative methods. Risk matrices can be developed and applied in the different stages of a project. The aim of ICDP is that PIs configure risk matrices that cover the whole project development (Initiation, Planning, Execution, Evaluation, Finishing) and to include them in their proposals to ICDP.

ICDP leaves it to the PI to select a preferred method to set up a proper risk analysis as far as the presented method accomplishes the risk management process of ISO 31000 and the ICDP tier levels. With the latter, drilling projects are classified internally into three categories according to the associated risks (Fig. 3.7.2):

- **Low Tier** are drilling and coring operations of less than one km depth with no casing sections, no open hole tests or other complex downhole operations
- **Medium Complexity** drilling operations comprise up to two km deep drilling, simple casing and one stage cemented sections, no completion strings, no long-term downhole monitoring installations.
- **High End** projects are deep drilling projects that go deeper than two km, have two or more casings and multistage cementing operations, directional drilling sections and so forth. Special attention is put on wells drilling across sediments due to the probability of hitting overpressured formations, well kicks, wellbore collapse, stuck pipe, gas presence. In this tier level ICDP will request a complete quantitative risk analysis with detailed management plan including contingency plans (Fig. 3.7.2).

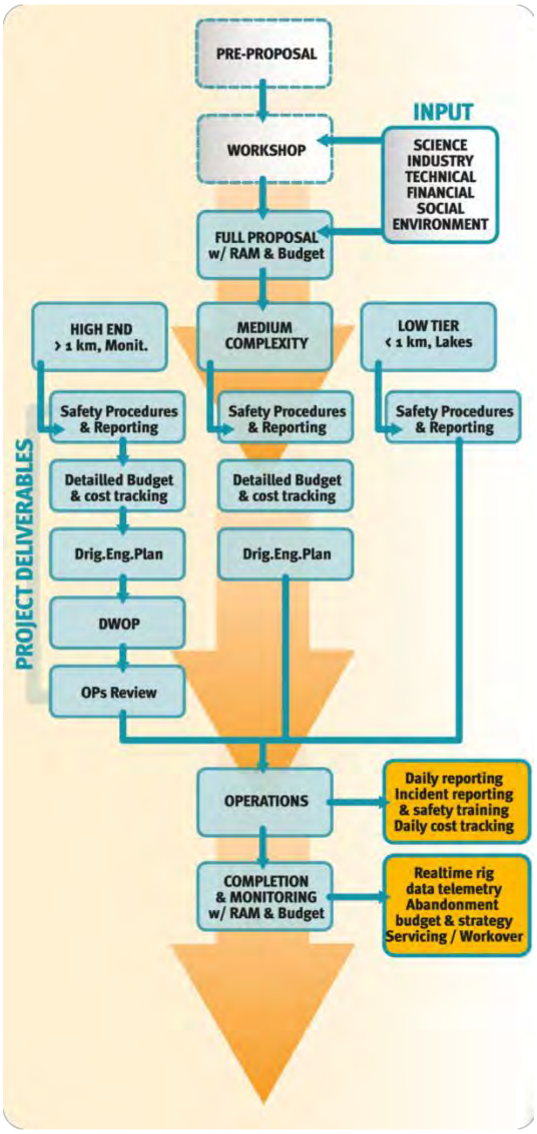


*Fig. 3.7.2: Risk management for ICDP projects; see text for detailed description. (RAM: risk assessment matrix; DWOP: drilling well on paper); Ops review: post drilling operational review)*

A recommended best practice is to use qualitative evaluations to set up individual risk assessment and analysis matrices. In general, a risk matrix includes potential hazards and threats that put personnel health and financial or technical integrity at risk. It shows the consequences induced and how to mitigate, minimize, avoid, eliminate or even tolerate them.

A qualitative risk assessment by using a matrix system identifies 'Potential Risks', classifies their 'Likelihood' and 'Impact' and estimates the resulting factor of a 'Risk Potential'. For each risk level, a 'Mitigation Strategy' must be developed and their 'Probability', as well as 'Impact Severity', re-estimated after a 'Mitigation Strategy' has been applied.

An example of a risk matrix analysis is shown in Table 3.7.1 with focus of geologically induced drilling risks for two borehole sections. Further matrix examples including some general risks for Scientific Drilling projects are provided in the Supplements to this Primer. In these matrices a traffic light system is used to highlight high, moderate, or low risks before and after countermeasures have been identified.

Table 3.7.1 addresses the issue that almost all drilling operations require to deal with drilling risks, such as unknown aquifers with fluid over- or underpressure, unexpected lithologies, borehole deformation, or tool failures. These risks may lead to uncontrolled situations that can jeopardize safety, health and the project at large. Therefore, they should be identified and remedies should be assigned beforehand. ICDP panels require the development of such matrices for all full proposals to ICDP. Once the project planning matures, specific drilling risk matrices should be further developed with input and counselling from personnel with operations, engineering, and scientific experience. In addition to drilling operations risks such matrices may address health, safety, and environment (HSE). These documents should already be prepared for the full proposal but will support project management through the operations. Thus, they need updates once the drilling contractor and equipment has been determined and detailed planning is at hand.

| Section | Stratigraphy | Geological Challenge | Scenario to Evaluate | Likelihood | Damage | Risk Classification | Preventive Actions | Likelihood after Prevention | Resultant Damage | Minimized Risk |
|---|---|---|---|---|---|---|---|---|---|---|
| Conductor casing (0 – 50 m) | Quaternary & Tertiary | Hardrock boulders | Hard formation, poor bit performance, low core recovery, time delay: 1 day | Probable | Low | | Pilot hole drilling with small diameter bit, use of low flow rates and bentonite mud | Low | Low damages in bit | |
| Casing (50-1000 m) | Tertiary | Boulders and sediments, adverse stress orientation | BHA verticality, impossible to core more than 1 m | Probable | Low | | BHA packed w/ 2 stabilizers, mud with bentonite | Low | Low damages in drill string | |
| | Jurassic | Swelling clays and shales | Bit balling, stuck pipe, low rate of penetration, poor coring, time delay: 1 week | Probable | High | | Mud combines with inhibitors, cleaning pills | Low | Damages in drill string and bit | |
| | Triassic | Unconsolidated sediments | Loss of fluids, stuck pipe, gas inflows, hydrocarbons presence, poor coring, 1-week lost time | Probable | High | | Increased mud weight, use of inhibitors, polymers, circulation schedules, controlled drill parameters | Low | Surface equipment damage, drill string damage, bit damage | |
| | | Swellable clays and shales | Bit balling, stuck pipe, low rate of penetration, time delay: 1 day | Probable | Low | | Mud combined with inhibitors, cleaning pills, learning curve | Low | Damages in drill string and bit | |
| | | Intrusive magmatics | Bit damage, loss of circulation, lost BHA, no core | Probable | High | | Changed bit, slowed rotation, less weight on bit | Low | Bit damage | |

*Table 3.7.1 Example of detailed drilling risks and related geological conditions analysed in a matrix for two well sections of a drilling project*

| | | | Very Unlikely >5% | Unlikely 5%-25% | Very Likely 25%-65% | Probable 65%-95% | Almost Certain >95% |
|---|---|---|---|---|---|---|---|
| | | **Case** | **Probability of Occurrence** | | | | |
| **Damage Extent** | **Severe Damage** | >3 months delay, serious injury, >65% adl. costs, loss of well, environmental damages, lost reputation | | | | | |
| | **High Damage** | >1 month delay, injury, high 15%- 65% additional costs, loss of well section, side track, fishing | | | | | |
| | **Middle Damage** | >1 week delay, minor injury, 15%- 35% extra costs, missing well section, side track, fishing | | | | | |
| | **Low Damage** | >1 day delay, 5% -15% extra cost, missing a well section, fishing | | | | | |
| | **Very low Damage** | Low time loss, lower additional costs (<5%) | | | | | |

| | |
|---|---|
| Risk acceptable, no necessity to minimize/eliminate risk potential | |
| Risk to be lowered as reasonably practicable, careful evaluation | |
| Risk intolerable, must be eliminated/reduced by minimizing impact of damage and likelihood of occurrence | |

*Table 3.7.2: Damage Extent vs Probability matrix for drilling projects*

In a further step, the red, magenta, and green traffic light system as shown in the Table 3.7.1 can be quantified by defining risk classification and risk mitigation in a matrix that categorizes the probability of occurrence versus the extent of the expected damage along major percentage steps as shown in Table 3.7.2.

An important instrument for identifying drilling risks in great detail is the so-called 'Drilling Well On Paper' meeting with representatives from all involved contractors and parties to discuss all operational steps and each procedure in all facets along the timeline. The outcome of such a pre-spud-in workshop will be a 'well on paper' document or operational plan. Well planning documents (drilling engineering document) and 'well on paper' documents (operational summary procedure) are part of deliverables that should be specified in the quality management plan and are helpful to improve risk matrices. The ICDP Operational Support Group (OSG) can provide support to science teams and PIs to set up such planning and will review the Well Planning, HSE & Drilling Operations Matrices and the Operational Plan independently.

CHAPTER 3.8

# Procurement Project Management

**Santiago Aldaz**

Procurement management supports project supervisors to identify and purchase goods or services needed for the project development. It follows pre-established guidelines, agreements, policies and/or standards. The PI and the stakeholders should be conscious at early stages of the project conception which services, tasks or products are available from within the science team and which have to be contracted externally from the service industry or other commercial vendors. Key examples for early decisions to be made are:

- Does our team need external project management service and support already for the project conception?
- At which phase of the project will we need to hire external support?
- Will external assistance be helpful for the submission of funding proposals to ICDP and other agencies?

The more detailed a scientific drilling project matures, the higher the value of already quantified resources needed is to reach the project objectives in time and budget. In fact, it is recommendable to follow the management concepts laid out in this chapter in a workshop proposal to ICDP already and to expand this in the full proposal.

Procurement management isn't a simple task, especially if a drilling project takes place in a region where local regulatory policies, supply chains, availability of required tools, services and costs are unknown. It will be necessary that a detailed procurement plan is previously organized and synchronized with ongoing drilling operations, is continuously updated and ahead of schedule to avoid non-productive time and waste of project resources.

Project procurement management as described in the literature consist of the three processes (Fig. 3.8.1):

1. **Plan Procurement** is structured in the planning phase, when it is necessary to identify which resources will be procured, to define the supplier profiles and to source the availability of e.g., tools, services, logistic, storage.
2. **Conduct Procurement** is the execution process when suppliers of services, logistics, and goods are selected to evaluate availability and capability, to define contract stipulations, and to arrange financial agreements in line with the expectations for operations. A functioning supply chain maintained by trusted service partners is crucial.
3. **Control procurement** comes into play once contracts have been awarded to the selected providers. In scientific drilling projects industry offers a wide variety of contracts. Usually, the fee for performing the contract objectives is calculated in relation to the risk involved in the project execution including or excluding insurances for environmental remedial, blow outs or lost in hole tools.

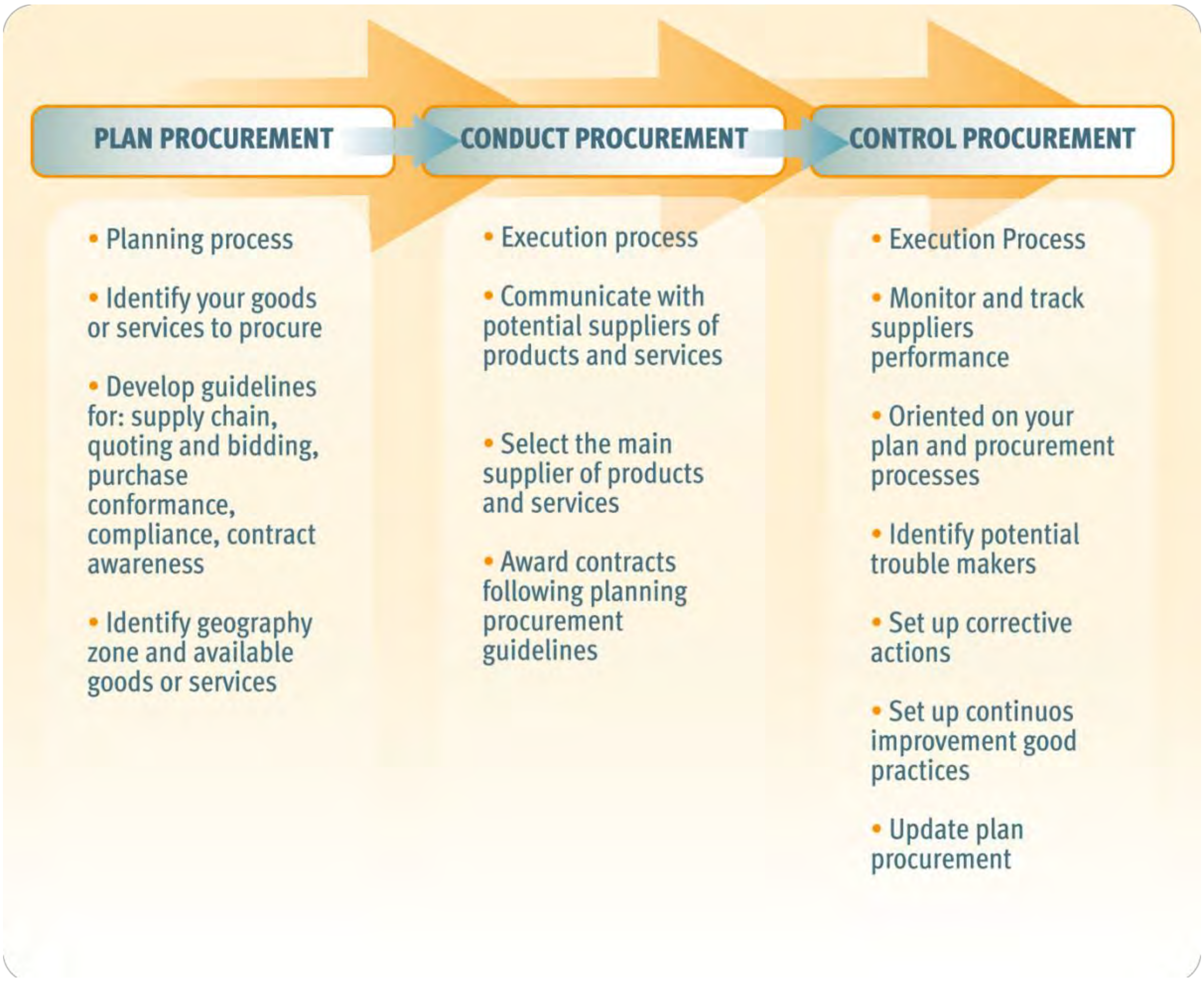


*Figure 3.8.1 Project Procurement management*

The most important purchase order placed in a drilling project will be the contract for drilling services, said contracts can be categorized according to different principles:

**Turnkey Drilling Contract:** The drilling contractor assumes the whole risk and responsibility to drill and core the well, for side tracks or even for abandonment and restarting a new well. The contract might include also the completion phase and remedial activities after ending drilling, coring, testing and completion operations. Liability and compliance to governmental laws will be compulsory for the drilling contractor and or shared with the project owner. Turnkey contract tariffs and costs are undoubtedly the most expensive ones.

1. **Daily Drilling Contract:** The project hires a drilling company for the period of time required to drill and core the well. The fee is calculated by time required for drilling operations. This rig fee might include crew costs but no field services provided by other companies, such as casing running, cementing, coring, bits, drilling fluids, well logging, testing. The liability and compliance to local regulations, policies, and governmental guidelines is obligatory for the drilling contractor.
2. **Footage Drilling Contract:** the project owner hires a drilling contractor and is paid to reach, drill, or core a specific well section or depth. Liability and compliance might be shared or totally transferred to the drilling contractor. This kind of contract relieves the

project owner of a time-based drilling performance but one needs to bear in mind that if not all field services are agreed upon, the project owner must cover additional rates or stand-by rates to the services companies.

3. **Integrated Project Management (IPM):** The management of the well planning, execution and operations supervision is assigned to an engineering company or integrated project management company. The IPM will commission the rig contractor, field services companies, environmental companies, and all required goods and services to drill, core, evaluate, test, and complete the well. The liability and responsibilities for compliance of local guidelines and operations execution will be previously agreed with the IPM company, and risk transfer, as enunciated earlier, will be a measurement parameter that determines the contract fees.
4. **Combined Services:** the project owner has the advantage of combining IPM services, daily footages and daily contracts. The liability to local policies is agreed upon among the project participants according to their assigned tasks.

Overall, control procurement is a process during the execution phase to monitor and follow the contract performance in compliance with all clauses, agreements, guidelines, and specifications agreed upon with service or contract providers. Drilling managers should proactively survey the companies contracted on a daily basis and take any corrective actions to keep the project on track as planned. The best approach for a scientific drilling PI is to interact continuously e.g., on a daily basis with the assigned company man and field services representatives to ensure that proper communication, tasks and goals are completed as planned in order to remain in budget and time, to ensure quality, to minimize risk and to optimize resources.

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CHAPTER 4.1

# Pre-site survey and site selection

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Once the scientific objectives of a drilling project have been defined it is necessary to locate the borehole, or boreholes, as optimally as possible. This can be a challenge due to logistical reasons, including constraints on the capability of acquiring the necessary site characterization data. The optimally located drill site should be well documented and motivated by scientific evidence (from site surveys) that allows for the scientific targets to be reached. The proper geoscientific documentation will allow well-founded drilling planning, engineering and thus minimize unexpected surprises for the drillers. Furthermore, the drill site needs to provide sufficient space for all operations or anchoring options for lake drilling that are planned on-site, fulfill logistical and environmental requirements and it has to be objectively safe, i.e., the risk for natural hazards and factors like climate and weather need to be manageable. In addition, elements like land ownership, access to lakes, public opinion and contact to authorities have to be considered. In addition to the reasoning for drilling, site selection, and permitting, the site survey has to address aspects of safety, environment and health for all drilling-related procedures.

## CRYSTALLINE BASEMENT SITE SURVEY

In this section we discuss how to deal with the multitude of requirements and select a suitable drill site for hard rock drilling on land. We start by discussing data on a regional scale that in many areas are already available and then move to a local scale for more specific site investigations and show examples from the Collisional Orogeny in the Scandinavian Caledonides (COSC) project. Some methodologies not employed directly in the COSC project are also discussed since we consider that they may be important for other hard rock drilling projects. Finally, we present the site selection strategy as it was used in the COSC project for locating the already drilled COSC-1 borehole (2.5 km deep) and the planned COSC-2 borehole (2.5 km deep).

### Geological maps, models and data

Scientific drilling projects are initiated because of a broad range of research ideas and drilling targets. The bedrock geology may play a primary or a secondary role for locating the drill site. For example, the local bedrock geology is the key for finding the best spot for the detailed investigation of a certain stratigraphic sequence, while it is less relevant for siting a borehole that aims to investigate a recently active fault segment. Whatever the target is, the scientists have to know the regional geology and obtain as detailed as possible geological information about the subsurface.

- Geological maps at various scales, usually issued by the national geological survey, provide the most comprehensive summary of the geology at the surface. They are essential for interpreting the regional structure and for planning and interpreting the geophysical site investigations. Not all areas are covered by published maps at an appropriate scale, but a search in the archives of the geological survey may produce valuable additional information, such as unpublished maps, outcrop maps and field notes. The geological literature may also contain studies that include large-scale maps. If the area has been of interest for mineral exploration then maps may exist at mining and exploration companies that can potentially be released.
- Multidimensional geological models are becoming more common, in particular in areas with substantial interest in the subsurface (construction, mining, cities, etc.). Depending on the country and location, these models might be maintained by the geological survey, a company or research institute. After positive evaluation of a model's base data and conditions, it can be used for drilling planning and, if necessary, the planning of additional site investigations.
- Databases of various kinds exist at the geological surveys (and possibly industry) that may include useful information for the planning and interpretation of site investigations, like structural data, age data, and physical rock properties.
- Existing boreholes in the region around the intended drill site provide information that has to be integrated in the planning of the new borehole, including detailed geology and indications about the stress field and borehole stability, which can be useful for comparison with the newly drilled borehole (downhole logging, e.g. temperature). The geological surveys usually maintain databases on wells, boreholes and, possibly, drill core. Contacting well-established mining and prospecting companies with current or former interest in the area might also help with locating relevant boreholes and drill core.

With recent developments in data infrastructure and data exchange, geological data become increasingly available. Many, but still not all, data sets hosted by governmental authorities (like geological surveys) in the European Union have become accessible, or at least discoverable, via the INSPIRE Geoportal. The up-coming European Plate Observing System data infrastructure (EPOS-ERIC) will provide harmonized access to solid Earth Sciences data from Europe. Similar initiatives may exist outside Europe.

**Topography**

Just one to two decades ago, topography was usually based on the analysis of aerial photography and classical land surveying; accurate to a few meters, but only available as contour lines on various maps and thus, mostly useful for interpreting geological structure and for the planning of surveys and logistics. The increasing availability of digital elevation models, initially mainly derived from (nearly) global satellite data (e.g., SRTM and ASTER GDEM, 1 and 0.5 arc second gridded data, respectively), made the integration with satellite/aerial imagery and other geosciences data more attractive. During the last few years, high-resolution/high-accuracy topography data acquired in airborne lidar surveys (up to 30 cm ground resolution, with a few centimeters vertical accuracy) have become available in some countries, even as open data (Fig. 4.1.1).

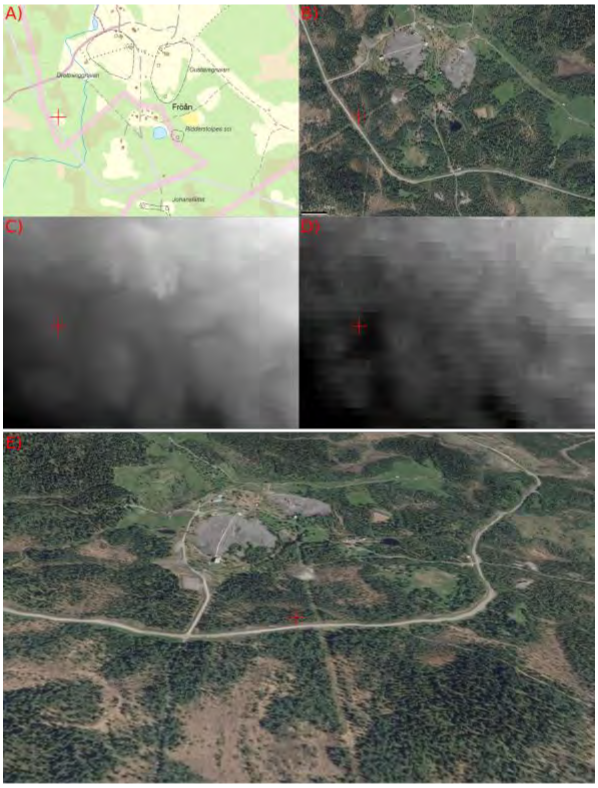


*Fig. 4.1.1: The COSC-1 drill site (red cross), constructed in 2013, in different data sets. A) Modern (digital) high-resolution topographic map (compiled for scale 1:10000). The drill site is marked as open space. B) Aerial imagery, orthophoto with 50 cm spatial resolution. The imagery was acquired before the drill site was constructed in 2013. C) Swedish national elevation model "grid 2+" (with 2 m spatial resolution). This digital elevation model is derived from a lidar data set that was acquired after the drill site was constructed. The road, the drill site and other infrastructure from the abandoned Fröå mine are clearly visible. D) Aster Global Digital Elevation Model (GDEM) with a resolution of 0.5 arc seconds (approx. 15 m along great circles). Features like the road can only be guessed. E) The orthophoto of (B) draped over the DEM (C), 3 times vertical exaggeration. Sources: A), B), C) © Lantmäteriet (Swedish Cadastral Agency); D) ASTER GDEM is a product of METI and NASA.*

This last step has opened completely new perspectives for the utilization of topography data, for example: analysis of surface features in a geological context (e.g., fault scarps); precise correction of geophysical data sets for topographic effects; improving the evaluation of objective risks; scouting in rough terrain for optimal site survey locations/potential drill sites/logistical access. In areas that are not covered by modern lidar data (i.e. most of the Earth's land surface), large scale topographic maps (if available) and quality controlled digital elevation models from satellite data are still the best option for providing topographic information in the preparations for a drilling project.

**Potential field data**

Potential field data, primarily gravity and magnetics, may provide information over extensive areas. These data have generally been acquired by geological surveys via a series of campaigns. In the case of gravity data the acquisition may have been over numerous years and the updating of the database with new measurements represents an ongoing process. This is because gravity data sets are acquired by point ground measurements, which is a slow process. Regional magnetic data are generally acquired by airborne surveys that cover large areas at one time. Even though airborne magnetic surveying is efficient there may still be significant gaps in a country's coverage.

Given the nature of the measurements and the fields themselves, magnetic data will almost always have a higher spatial resolution compared to gravity data. However, gravity data will be more sensitive to anomalous material deeper in the crust. Under certain conditions, both can be used to determine the depth to the anomalous material. Gravity data are simpler to interpret since the gravity field is a scalar that is determined by the density distributions in the Earth, while 26 the magnetic field is a vector field that is dependent upon the Earth's internal field, the induced field, and the remanent magnetization in the rocks.

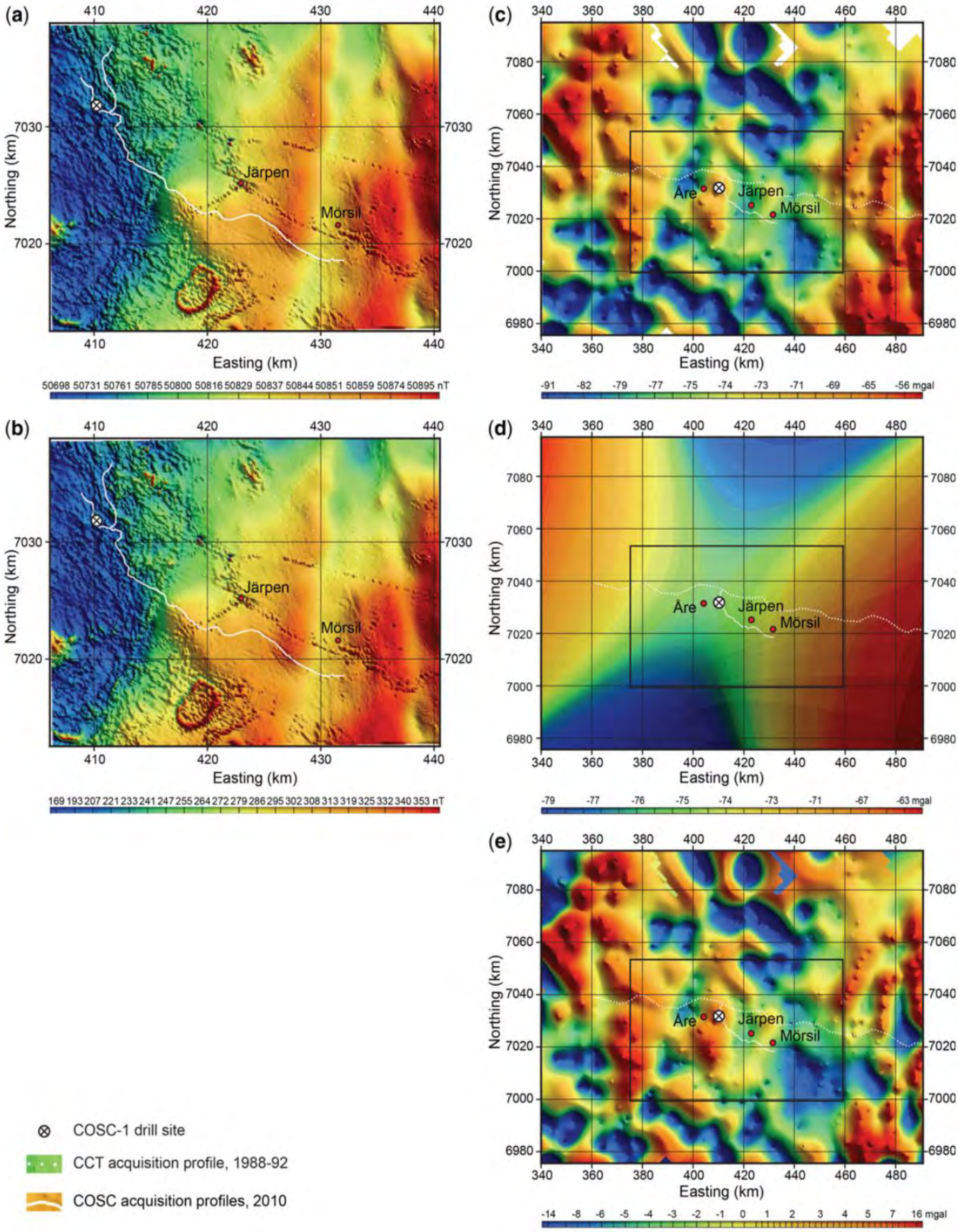


*Fig. 4.1.2: (a) Observed total field aeromagnetic anomaly; (b) residual magnetic field after removal of the magnetic reference field (DGRF); (c) observed Bouguer gravity anomaly; (d) regional gravity field; and (e) Bouguer-residual gravity field. The black rectangle shows the extent of data used in the inversion modeling of Hedin et al. (2014).*

For interpretation of both types of data it is necessary to make a number of corrections to the raw data. An important correction, and often the most challenging, is the removal of the regional field to produce a residual field that can be used as input into modeling and inversion software.

**Seismicity**

In some hard rock areas seismic activity may be an important consideration in locating a drill site. Many geological surveys, or other government organizations, will have historical databases on seismicity within the country's borders. If the objective is to drill into an active fault then these databases are probably not accurate enough for locating a borehole. Local detailed networks would need to be established to determine earthquake locations on a more accurate scale. However, the seismicity maps provide information on what precautions need to be taken concerning the safety of the drill rig and on-site personnel.

**Objective hazards**

Objective hazards can pose a direct danger to the drill site, the on-site crew and the drilling operations and they can lead to a failed project and a missed drilling target due to severe delays, increasing costs and premature termination of the drilling operations. Examples are unexpected storms, high precipitation, high/low temperature, an early cold season, avalanches, rock falls and landslides. When you chose your drill site, make sure that you know under which circumstances your operations are possible. Check for known risks (natural hazard maps, surrounding topography) and investigate the long-term weather statistics with extreme values. Talk to locals and consider their experience.

**Seismic refraction surveys**

Seismic refraction surveys provide information on the velocity structure in the underground. For them to be useful there has to be an increase in velocity with depth in order for the rays to penetrate deeper into the bedrock. For target depths of a few kilometers this is usually the case in sedimentary rock areas. However, in hard rock areas, the gradient with depth can be very small and penetration may at best only be on the order of 100s of meters. The actual penetration of the rays depends on the local velocity structure and the maximum offset between sources and receivers. A very rough rule of thumb is that offsets of at least 10 times the desired depth of investigation are required. However, if dense receiver arrays are used for the refraction studies then wide-angle reflections can be detected from deeper levels, increasing the information content obtained from below the site.

**Seismic reflection surveys**

A primary aim of a seismic reflection site survey is to produce a seismic section that can be used for predicting what lithologies and structures will be penetrated from the near surface down to target depth. Given that the structure in the near surface is important for planning the drilling, high-resolution seismic imaging is necessary with a close spacing between the sources and receivers. 3D surveys are highly desirable, but the cost of such surveys in forested and mountainous areas usually prohibits their acquisition. Therefore, 2D data are commonly used in site investigations. Even though only 2D, efforts should be made to acquire 3D structural information near the drillsite by either

- acquiring crossing lines (short line(s) that cross the main seismic line more or less perpendicular close to or at the intended drill site) or
- performing a cross-dip analysis of "crooked line" data (e.g. Nedimovic and West, 2003), or

- processing the acquired "crooked line" data in pseudo-3D (e.g. Malehmir, 2011).

The latter two methods utilize the deviations of the acquisition line from a straight line, e.g. due to the course of a road, to extract limited 3D information.

For locating the COSC-2 borehole, seismic data were acquired with a receiver spacing of 20 m and a source spacing of 20 m (10 m over some stretches) on about 350 channels. Data processing generally followed standard procedures with a resulting clear image. Since the reflections are quite distinct and generally sub-horizontal, the velocity analysis provides a reasonable function for time to depth conversion, resulting in a fairly accurate depth section for interpretation (Fig. 6.3). This claim is corroborated by the inversion of magnetotelluric (MT) data (Yan et al., 2017) that provide the depth to top of a conductive shale (the Alum shale) and magnetic data (Juhlin et al. 2016) that provide an estimate to the top of the magnetic basement.

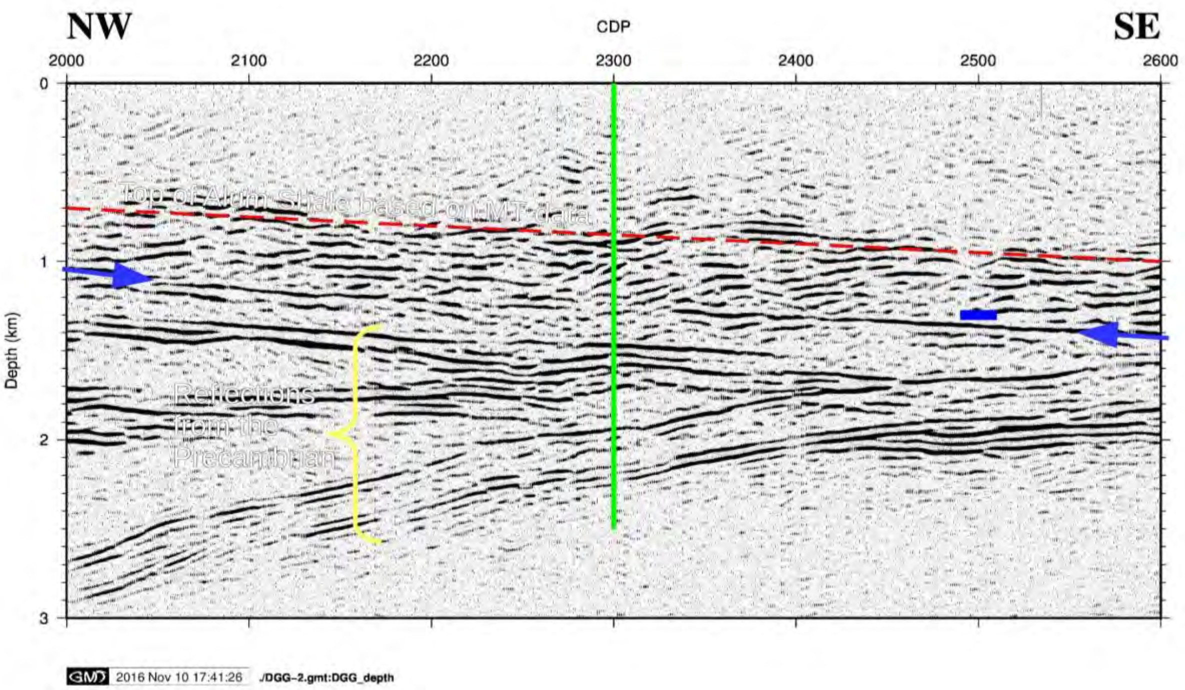


*Fig. 4.1.3: Detailed view of the seismic section (section based on Juhlin et al. (2016)) in Fig. 4.1.4 near the planned COSC-2 borehole (green vertical line). Red dashed line marks the depth to the top of the good conductor as determined from magnetotelluric data (Yan et al., 2017) and the blue line below CDP 2500 indicates the depth to magnetic basement based on modeling of the total magnetic field. The blue arrows indicate the surface representing the interpreted main Caledonian décollement. Reflections below 1.2 km are interpreted to originate from within the Precambrian basement (yellow curly bracket).*

**Magnetotelluric surveys**

Magnetotellurics (MT) is a geophysical method for investigating the subsurface electrical resistivity (inverse of conductivity) from measurements of natural geomagnetic and geoelectric field variations at the Earth's surface. Investigation depth ranges from 300 m below ground by recording at higher frequencies and down deep into the mantle by recording very long period signals (acquisition time in the order of a day or longer per station). If the audio-magnetotelluric (AMT) method is employed using higher frequencies, then shallower structures can be investigated at the cost of a reduced maximum penetration depth. AMT measurements often take only about one hour per station to perform and use smaller and lighter magnetic sensors.

For locating COSC-2, broadband MT data were acquired at 83 stations along the COSC seismic profile with a station spacing between 500 and 1000 m using 5 instruments. Three different sampling rates were applied: 20 Hz for ~21.5 hr, 1000 Hz for 2 hr starting from midnight and 3000 Hz for about half an hour during daytime, allowing both MT and AMT data to be recorded. Due to the high conductivity organic-rich Alum shale present along much of the profile the penetration is limited to about to 5-6 km, even less at some locations (Fig. 4.1.4). Longer period data would be necessary to allow penetration to greater depth. The broadband nature of the instrumentation allows shallow imaging, as well as deeper imaging at those locations where the Alum shale is less thick or less conducting.

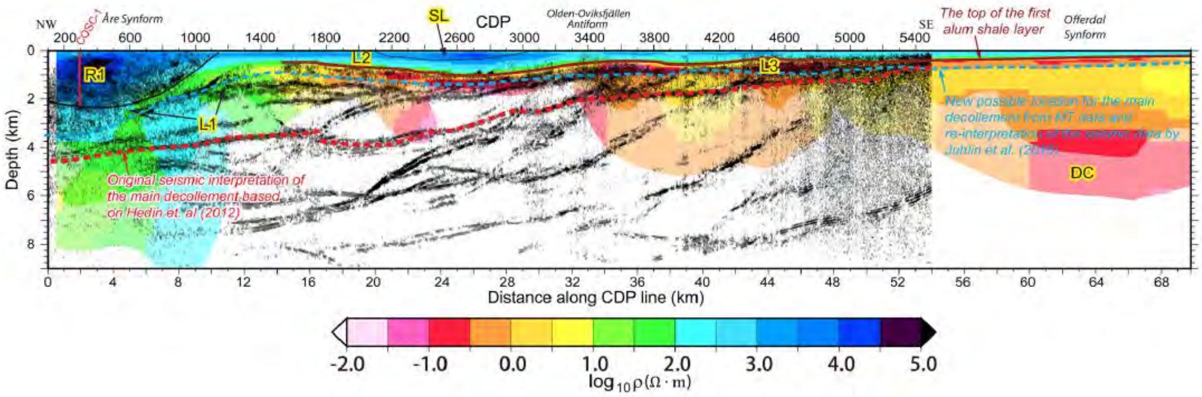


*Fig. 4.1.4: 2D resistivity model from Yan et al. (2017). The depth to the good conductor east of CDP 1500 corresponds very well to the top of the strong reflectivity in the seismic section. For details on interpretation see Yan et al. (2017).*

**Electrical Resistivity Tomography**

Electrical Resistivity Tomography (ERT) or Electrical Resistivity Imaging provides information on the resistivity structure at a site from the very near surface (a few meters) down to around 1 km in some cases. Normal penetration depths are in the order of 100s of meters. The measurements are performed by injecting either an alternating current (AC) or a direct current (DC) into the ground and by measuring the potential difference between electrodes at various locations on the surface (e.g. Dahlin, 2001). Penetration depth is governed by the distance between different electrodes and by the strength of the current source. Results may be frequency-dependent so estimated resistivities may differ from those measured by other methods. The method is relatively fast to employ and cost effective. It can complement AMT data at the site to provide images of the near-surface resistivity structure or be a substitute for AMT data if the latter are not available. In hard rock environment surveys, it can be employed to localize potential fracture zones (Fig. 4.1.5). ERT was not performed in connection with COSC project since the AMT/MT data provide excellent resistivity images, but the method should be considered for any site investigation.

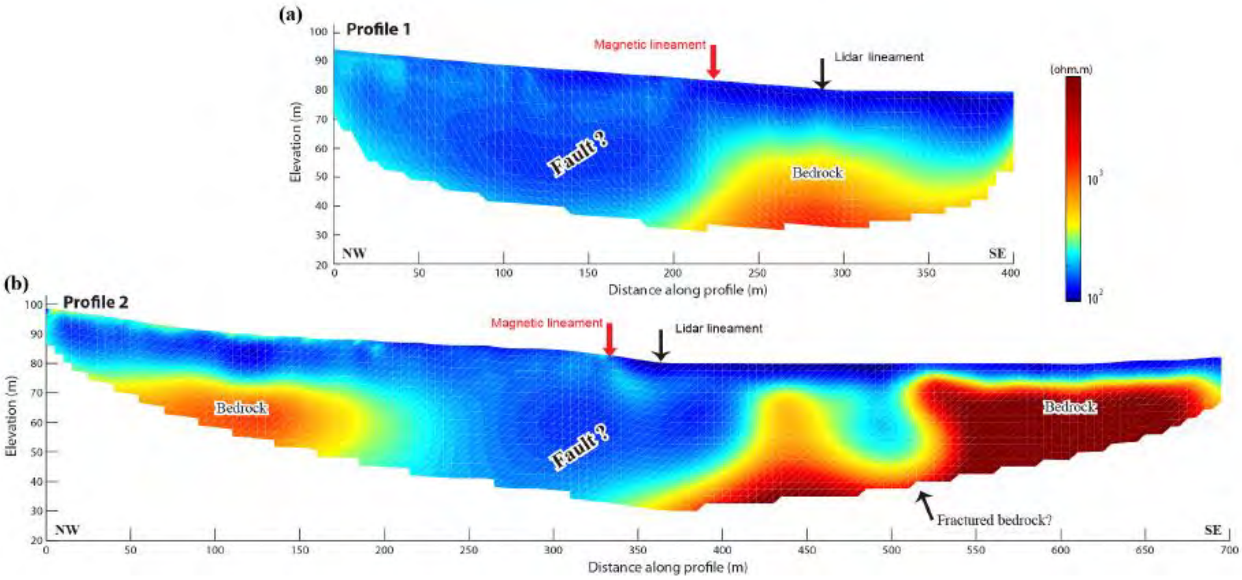


*Fig. 4.1.5: ERT results along two profiles from central Sweden consistently showing clear evidence of a conductivity structure west of a scarp. The data also suggest that the bedrock is shallower on the eastern side of the scarp than on its western side, consistent with magnetic and seismic results. Figure is from Malehmir et al. (2016).*

**Potential field methods surveys**

Acquisition of detailed gravity data and ground based (or drone/helicopter) magnetic data near the drill site may help in optimally locating the borehole. These methods will work best if there are lateral changes in density and/or magnetic properties at depth. Magnetic data may be particularly important if the bedrock is not exposed, for example covered with glacial sediments or regolith. Fracture zones in the bedrock can often be mapped as magnetic lows and mafic intrusions as magnetic highs. Figure 4.1.6 shows an example where interpreted lineaments clearly show up on a high-resolution magnetic survey. These lineaments appear as magnetic lows (striking mainly in the WSW-ENE direction) and crosscut the general trend (NW-SE) of the magnetic fabric.

**The site selection strategy**

The site selection strategy primarily has to balance the appropriateness of a site for fulfilling the project's scientific objectives against constraints put onto the project by the physical and legal conditions of the drill site. For example, infrastructural conditions such as lack of pathways for heavy trucks, availability of water or power can exclude a potential drillsite as well as permitting or public acceptance issues. The scientific objectives will determine possible locations for drilling along the site investigations. Not all potential locations will serve all scientific objectives equally well and the PIs have to decide how to prioritize. Often, the priority of scientific objectives is already defined by the main topic of a project while other scientific objectives are added-value and not crucial for the main mission. The PIs have to consult with each other and the geophysicists and geologists responsible for the site investigations and together identify and rank suitable drilling locations.

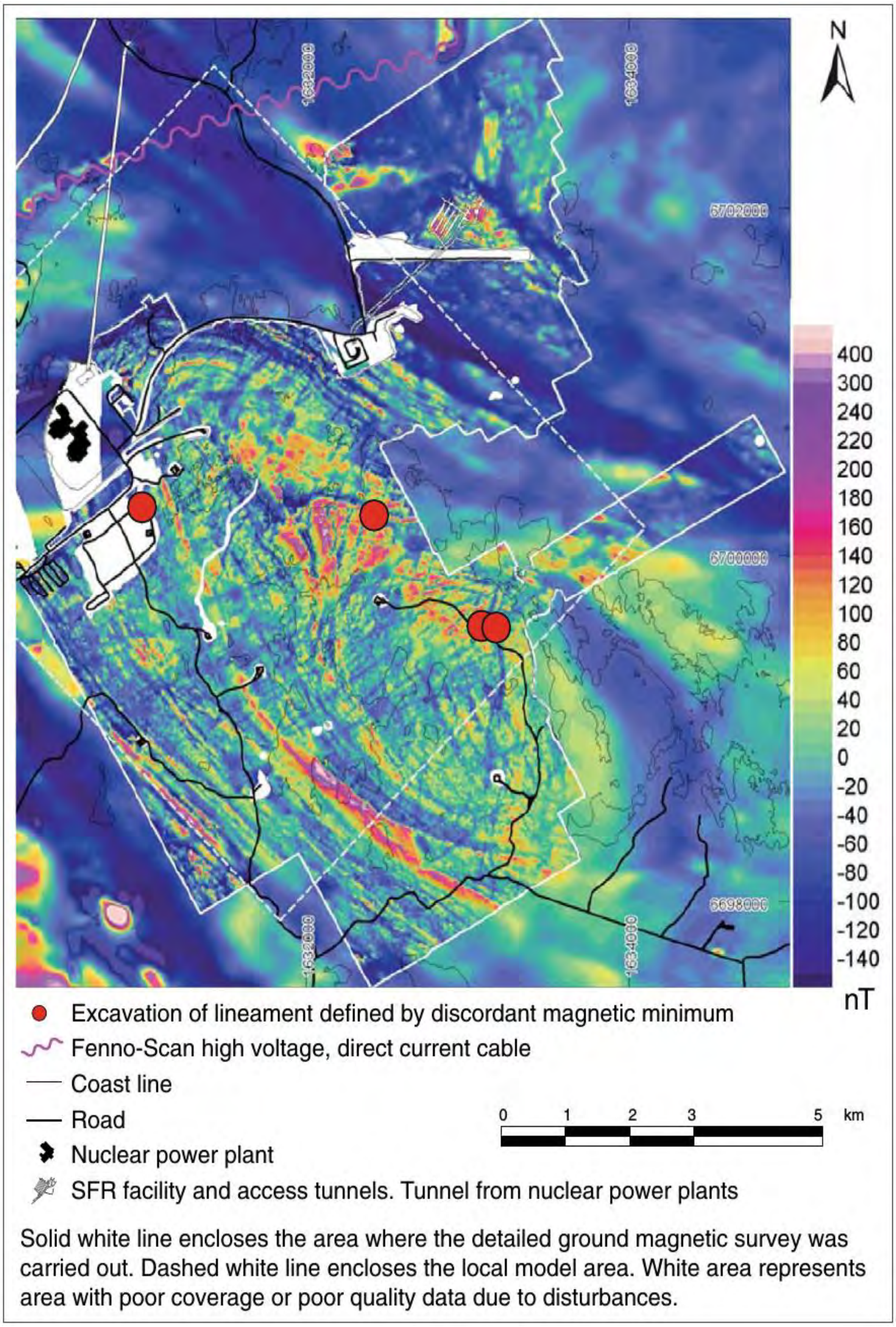


*Fig. 4.1.6: Integrated total magnetic field from Forsmark, Sweden, based on data from a helicopter airborne survey in a N-S direction and a high-resolution ground magnetic survey in a NNW-SSE direction. Units in nanoTesla [nT]. Locations of investigations of lineaments defined by magnetic minima are also shown. Figure is from Stephens et al. (2015).*

**Site selection restrictions**

After the establishment of a list of potential drilling locations with prioritization according to scientific targets, this list has to meet the reality of the field and a number of circumstances can disqualify a potential drill site:

- unsuitable terrain (e.g. too steep to build a sufficiently large drill site)
- objective risks (see section on risks above)
- to risky to drill (unsuitable geology for reaching the target)
- legal obstacles (location in national park, nature reserve, military area, water protection area, etc.)
- land owner consent not achievable
- negative public opinion
- and possibly others

**Access and infrastructure**

The type of access to a potential drill site and the existence (or not) of key infrastructure can have a severe impact on a scientific drilling project, as it may limit the types of equipment that can be deployed and at what costs. Key issues are road access, electricity and water, which the remaining potential drilling locations have to be tested against. Relocation of a drilling location with evaluation of the consequences for the scientific targets has to be considered seriously if access to infrastructure is not given in the prioritized locations.

Road access will allow comparatively cheap transports, including the transport of heavy equipment, and is essential for all drilling operations with large rotary ("oil-field type") drilling equipment. Other options exist for core drilling ("mineral exploration type"). If the drill site cannot be located directly besides an existing road, the construction of an access road is the preferable solution if costs/distance and regulations allow. Be aware of possible restoration/renaturation costs and how long after drilling the access to the drill site is required and possible. Deployment of a drill rig with off-road capabilities (e.g. crawler mounted) is another option if road access is not possible and if the terrain allows. However, be aware of more complicated and expensive logistics, in particular for heavy and specialized transports like drill pipes, tanks, fuel, mud disposal and drill core, and whether other essential scientific equipment can still be deployed under these circumstances. Deployment of equipment by plane and/or helicopter (or possibly boat) is the last resort if all other options prove impossible. Such specialized equipment and its transport is expensive and clearly restricts the achievable borehole diameter and depth due to weight and size limitations.

Electricity is required for many tasks at the drill site, some essential (e.g. operation of pumps, mixers, scientific real-time data collection, etc.), others optional (on-site science, heating, etc.). A connection to grid power is preferable and can solve all problems with regard to energy supply (ask the local energy supplier for the closest power line and options and costs to connect). In this case, include proper protection of your equipment against electrical damage and backup-power from a sufficiently large generator in your plans. In case grid power is not available, the alternative is two sets of generators, regular and backup, both of which independently with the ability to cover the maximum power. In the latter case, it may be reasonable to only have operations at the drill site that are absolutely essential and carry out other tasks, like core description, elsewhere. In any case, it is absolutely necessary to calculate the power needs at the drill site carefully and plan the power supply with sufficient margin.

Water is used in significant amounts at each drill site, mainly as borehole fluid. If you do not have clean water at the drill site or within a distance that allows pumping (either from a natural water body, a well or pipes), you have to bring it to the drill site by other means. In this case, road access will significantly ease operations and lower costs. Make sure that you know your water consumption levels during the drilling operations (including emergencies like fluid loss in the borehole) and that you have means to cover it.

**Logistics**

Logistics at the drill site vary widely from project to project, but can be subdivided into technical/drilling logistics and scientific logistics. Road access to the drill site will significantly ease logistics in all cases. If possible, let the operator and/or drilling/technical manager take care of the logistics for the drilling operations, since they have a much better perception of their needs and timing than any PI has. The main logistical points to be considered during drill site selection are summarized below.

- Design the drill site layout in close collaboration with the operator, usually before permitting. Make sure that you have enough working and storage space for your scientific on-site operations (if any) and that the selected location accommodates the size of the drill site.
- Construction of the drill site. Make sure that you have a reliable contractor who follows local regulations. Is site restoration after drilling required? Build accordingly.
- Identify a transport company that can serve you at the drill site reliably, even if the site is remotely located.
- Inform the public about your drill site and the operations/project.

**Permitting**

Permitting procedures vary widely, depending on the host country for the drilling, from complex procedures with several applications to different authorities (may include military) to a simple notification of drilling. Also, the type of planned operations (e.g., testing) may have an impact on the permitting. Investigate early what rules apply in your target area and initiate the contact with the responsible authorities. Make sure to have all required documents and studies ready in time (usually, an environmental consequence analysis and possibly a risk analysis are necessary). A positive attitude from the landowner will surely help. In some countries, and under complex circumstances, it may be beneficial to contract an engineering office for planning and executing the permitting process and possibly the operations at large.

**COSC-1 Site Selection**

Based on the site investigations, the wider area of an old mine, Fröå gruvor, was identified as the primary location for the COSC-1 borehole. The project leader, scientific and technical managers and chief driller met on-site and defined the most promising drill site in the area: directly besides an unpaved road, 400 m from a power line and with sufficiently clean water that could be collected and pumped from the ground. At the same time, contact with the municipality was established. The two affected landowners were positive to the project, but the drill site was moved slightly in order to only affect one landowner, in this case the municipality. Neighbors and the general public were informed in letters, advertisements and a sign at the planned drilling location. The technical management took care of the permitting process including the environmental consequence analysis and permission to construct the drill site. The latter happened during summer 2013. In late winter 2014, snow was cleared and the heavy equipment mobilized while the ground was frozen. Drilling operations lasted from May to August 2014, followed by extensive borehole surveys during the remainder of the year. The main logistical problems were unstable electric power supply from the grid during wet days (due to the long cable and its many connectors) and a load restriction on the unpaved road past the drill site during about 4 weeks in spring because of unstable, partly-frozen and water-saturated ground, which prohibited effective refueling of the tanks at the drill site and the disposal of drilling mud. The weight limitation on the road is annually recurring and precautions had been taken accordingly.

## LAKE SEDIMENT SITE SURVEYS

The following paragraphs highlight pre-site surveys for lake drilling campaigns. They typically combine geophysical imaging (especially seismics) with some shallow sediment sampling (usually gravity or piston coring).

### Regional surveys

Pre-site surveys include the compilation of all existing geological and geophysical data in a region. Geological maps, sample investigations, geophysical research and all other kinds of geoscientific information will be utilized to form a decision base for further research in more detail. The regional data compilation is necessary for putting the entire drilling campaign in a broader geological context and helps to identify potential areas, where the proposed drilling targets may be reached and which ones need to be investigated further. It is not always easy to get access to all available data, because old data are stored in analogue form, data archives are difficult to access, or metadata and reports are only available in the language of the country where they have been collected. Additionally, commercial companies may have worked in the area of interest and have collected high-quality data, but these companies are often not willing to share the data due to economic interests. However, it is of great importance to spend all possible efforts in the compilation of the available/accessible data because such a compilation helps to select the areas for targeted pre-site surveys and supports the drill-site selection; in addition, it can save time and money.

Despite the fact that there are no formal site survey requirements in ICDP it is extremely unlikely that lake drilling proposals will be approved without good seismic data imaging of the drill target with best possible quality and resolution. In lakes and similar depositional environments, seismic data have become a standard tool and must be acquired before drilling.

### Site survey

In general, site survey data have to fulfil a number of key criteria including that:

- detailed plans for drilling are based on an adequate site imaging using survey data
- the site is selected in a way that all key scientific questions can be answered
- the site is in a location suitable for the drilling method and the tools planned for
- the site survey information provided for the scientific review contains sufficient information to support both the science and the drilling operations

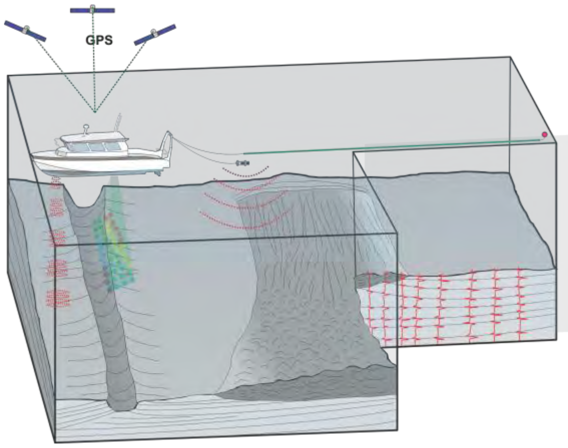


*Fig. 4.1.7: Potential setup for an acoustic lacustrine site-survey with multibeam bathymetry (left) sediment echo sounder (center), reflection seismic system (right)*

Site surveys in lacustrine environments usually comprise seismic imaging and the collection of short cores. Other data may be collected as well, e.g. bathymetric data and surface samples. In lacustrine environments, site survey data can often only be collected utilizing the available type(s) of vessel or platform with very limited amount of space and accordingly challenging data collection. A potential setup of a typical site survey is shown in Fig. 4.1.7.

**Bathymetric imaging**

Bathymetric data allow characterizing the morphology of entire lakes (Fig. 4.1.8) or selected areas (e.g. around proposed drill sites). Such data are useful for investigating modern sediment dynamics, which can be critical for site selection, e.g. to avoid areas prone to sediment transport causing incomplete sedimentary successions.

Bathymetric data are nowadays collected with multibeam echo sounders. These systems transmit an entire swath of beams giving off-track-depth. Modern multibeam systems also allow collecting backscatter data useful for characterizing the lake floor sediments. Typical opening angles of multibeam systems are up to 150° resulting in a swath width of up to 7 times the water depth. A multibeam system consists of a transducer, a motion-reference unit and a control unit. In addition, sound velocity profiles of the water column are needed because non-vertically traveling rays are refracted. This fact has to be taken into consideration during data acquisition and processing because otherwise the data would provide wrong locations and water depths. Mobile systems also have to be calibrated at the beginning of each survey.

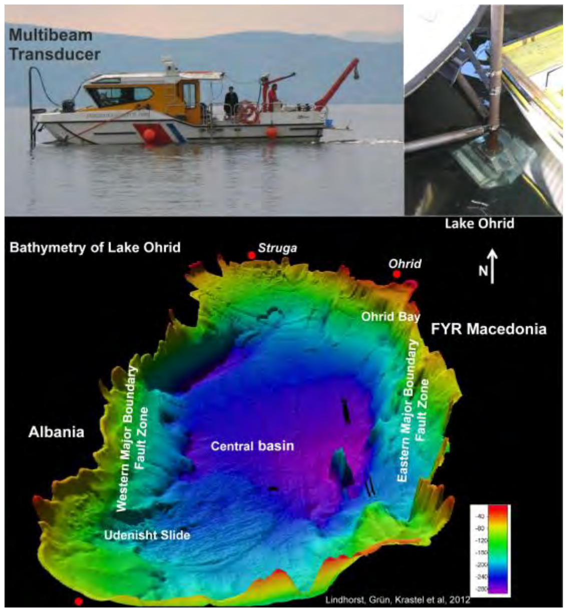


*Fig 4.1.8: Upper left: Multibeam transducer mounted at the bow of a small survey vessel. Upper right: Details of the multibeam transducer. Lower part: Bathymetric map of Lake Ohrid collected with a multibeam system (taken from Lindhorst et al., 2012)*

When acquiring multibeam data, the coverage is highly dependent on water depth. Only narrow swathes can be collected in shallow water (e.g., ~ 70 m wide swath in 10 m water depth), while larger water depths result in better coverage but reduced resolution as the same number of beams covers a larger area. In addition, mobile systems are often limited in their depth capability and it may not be possible to collect data across the entire opening angle and/or only up to a specific water depth.

**Seismic imaging**

Seismic imaging is the most important technique for site selection as it allows acquiring structural images of the subsurface down to meter-resolution. The seismic method utilizes sound waves, that are reflected and refracted as they interact with lithological boundaries e.g., in sedimentary strata beneath the lake floor. The methods are accordingly divided into reflection and refraction seismics. The reflection seismic method makes use of near vertical rays. They are reflected once the seismic impedance is changing e.g. due to a lithological contrast. The seismic impedance is sound velocity multiplied with density; the stronger the impedance contrast, the stronger the reflection. The impedance contrast may also be negative. This is often the case if free gas has accumulated in the pore space of sediments and reduces the sound velocity and density compared to sediments with liquids in the pore spaces. Accordingly, the reflection seismic method is also important for identifying gas occurrence, one of the utmost serious drilling hazards. In contrast, refraction methods recording refracted waves need large offsets between source and receiver. Typically, this technique is used to investigate large-scale layering. It is usually not detailed enough for precise drill site selection but it supports identifying major boundaries such as between lacustrine sediments and bedrock.

Instruments needed for reflection data seismic acquisition include a source, receivers and an acquisition unit. The source is mainly controlling the penetration and resolution. Large sources transmit energy at relatively low frequencies (< 80 Hz), which penetrate deep into the subsurface but the acquired images have a limited resolution due to the long wavelengths (10s of meters). On the other hand, high frequency sources have a very limited penetration (10s of meters) at a submeter resolution. Thus, the user always has to choose the right source in order to get the desired penetration at best possible resolution or, in other words, it is not possible to achieve deep penetration and high resolution at the same time. The highest resolution systems used for lake surveys are sediment echo sounders. One transducer is usually used for transmitting and receiving the energy. Typical frequencies are between 4 and 15 kHz corresponding to wavelengths between 10 to 40 cm. Nowadays, so-called parametric sediment echo sounders provide a much better horizontal resolution than conventional systems. These systems can be deployed even from very small vessels (Fig. 4.1.9).


*Fig. 4.1.9: Shallow water survey with parametric sub-bottom profiler SES-2000 consisting of a transducer and a control unit and consuming less than 500 W (© Innomar Technologie GmbH 2006)*

Systems for deeper penetration usually have separated sources and receivers (Fig. 4). The former include boomers, sparker, chirps and airguns. Airguns are the most common source if penetration of more than 100 m is needed. Airgun profiling is a standard tool in marine geophysics, but for lacustrine surveys the systems have to be minimized for deployment on small vessels (Fig. 4.1.10).

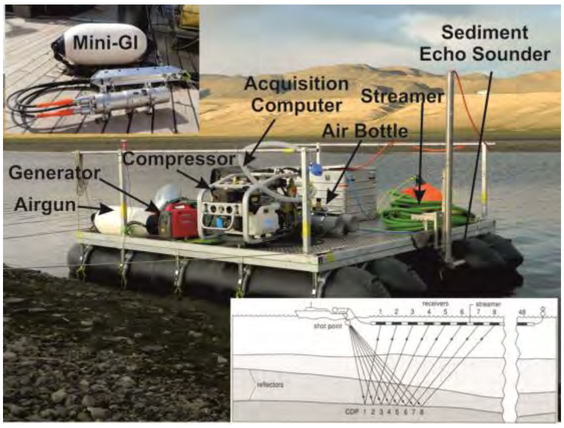


*Fig. 4.1.10: Setup of an airgun reflection seismic system consisting of a Micro-GI Gun (modified Mini-GI Gun), a single mobile diving compressor, an air bottle for intermediate storage of compressed air, a 50-long 32 channel digital streamer and an acquisition system; upper left: image of a Mini-GI gun; lower right: principle of seismic reflection profiling.*

An airgun consists of a chamber for compressed air that can be rapidly released in order to generate an acoustic pulse into the water column. The volume of the airgun controls the frequency and energy. Chamber volumes between 0.1 and several 10s of liters are available. Compressed air (around 150 bar) needs to be provided by compressors on board. Due to the small vessel sizes available for lacustrine surveys, usually only small guns can be handled during site surveys. A common type of airgun used for lacustrine surveys is a Mini-GI Gun (Fig. 4.1.10). GI stands for Generator-Injector. The generator produces the primary pulse while the injector injects a pulse of air into the bubble near its maximum expansion. This second pulse dampens undesirable secondary energy produced during expansion and collapse of the bubble. Standard volumes of Mini-GI guns can be easily changed from 0.25 l (15 cu.in) up to 0.5 l (30 cu.in). The user has to remember that almost twice the compressed air is needed when using a GI-Gun instead of a conventional airgun.

The energy is recorded with a streamer (Fig. 4.1.10), a cable towed behind the vessel with a large number of hydrophones. This setup covers the same point with different source receiver pairs allowing the so-called CMP-stacking, which enhances the signal quality.

In order to optimize resolution at different depth levels, seismic data sets with different frequency contents can be collected at the same time. It is very common to combine airgun seismic profiling with the acquisition of sediment echo sounder data (Fig. 4.1.11).

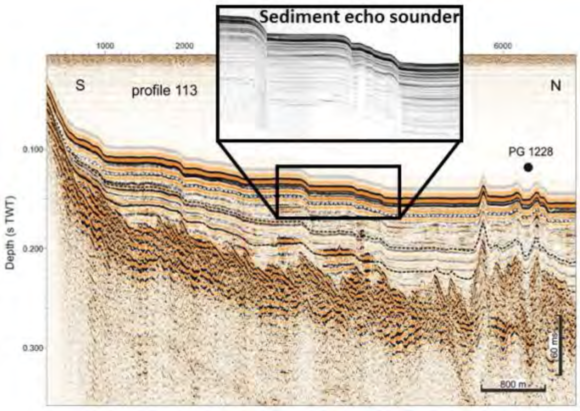


*Fig. 4.1.11: Comparison of airgun seismic and sediment echo sounder data. Note the different resolution and penetration. The data have been collected with the system shown in Fig. 4.1.10.*

After data collection, the records need to be processed. Processing of reflection seismic data can be very time consuming and quite some efforts are needed to optimize the imaging quality. Critical steps for the processing are optimizing the resolution and the suppression of multiple and other unwanted energy. Multiples may mask deeper primary reflections especially in shallow water conditions. Although seismic processing methodologies are constantly improved, multiple suppression of high-resolution data in shallow water is not a standard processing step and requires very skilled personnel for in-depth analyses.

3D-seismic data acquisition is now a standard tool in industry and is also more and more utilized by academia. Some academic systems permit collecting ultra-high resolution 3D-seismic data with very limited penetration (10s of meters). 3D-seismic systems penetrating more than several 10s of meters cannot be deployed from small vessels, such as the ones usually available on lakes, but require large marine research vessels. Hence, advanced 3D-seismic data have so far not been collected on lakes.

The acquisition of refraction seismic data requires a large distance between source and receiver. Such a setup cannot be achieved with a towed streamer system but sonobuoys (free-floating hydrophones) or ocean bottom seismometers (OBS) need to be deployed. Sonobuoys transmit the recorded waves by radio or store the data for read-out after recovery. It is also possible to place OBS recorders on the sea floor. The deployment of these OBSs is usually difficult from small vessels but recently developed Mini-OBS serve the job. Structural resolution is usually much better with reflection seismic data. Hence, refraction data are not as critical for drill site characterization. However, the velocity information is much better from refraction seismic data so that they aid in determining drilling depth as fundamental factor for drilling planning and permitting.

**Shallow coring**

Obtaining short lacustrine sediment samples during a site survey can provide pivotal information including quality of paleo-environmental proxies recorded in the sediment archive, geochronology, sedimentation rate as well as site selection criteria.

*Fig. 4.1.12: Platform for taking shallow piston cores*

In order to understand recent sedimentation patterns of an investigated lake, a grid of surface samples can be taken using small gravity corers or grab samplers, easily operated from small vessels. The sedimentological (e.g. grain size) and geochemical analyses (e.g. elemental composition) of these surface sediments allow charting the spatial sediment variability. Thus, the influence of lake internal transport processes and of the different catchment geology on lacustrine sediment deposition can be explored (e.g., Wennrich et al., 2013). Lake internal current systems can cause frequent sediment transport in specific areas of a lake resulting in incomplete or disturbed sediment successions. Accordingly, pilot studies on shallow cores covering e.g. the last thousands of years can provide valuable information for drill site selection and sequence interpretation. Age information on shallow cores delivers sedimentation rates and allows a projection of age-depth estimations for the entire potential record. Studying the sediments of known past climatic conditions (e.g. glacial/interglacial sediments) enables testing and developing paleo-environmental and -climatic sensitive proxies for the local system, that can be transferred to a potential deep drilling record later on. Additionally, by knowing the sediment characteristics, suitable deep coring methods and tools can be considered.

First seismic results (e.g., sediment echo sounder data) are usually used for the selection of short coring sites in order to identify undisturbed and continuous sediment successions. Common and established tools for obtaining such shallow cores in lakes are gravity corers (0-3 m) or piston corer systems (0-30 m), which are operated from small floating platforms equipped with a tripod or A-frame (Fig. 4.1.11). Gravity corers provide the most undisturbed samples of the topmost centimeters of the sediment. For each run, their assemblage is equipped with a plastic liner (0.5-3.0 m) and weights adjusted to achieve the desired penetration depths. Longer sequences are usually obtained by a piston corer, which is hammered into the sediment. A piston at the bottom of the corer seals the coring chamber (2-3 m long) until it is released via wire cable in the preferred sediment depth of which the core shall be taken. For each run, a new borehole has to be started and the cores of several runs with overlapping depths are composed to a continuous sequence.

**Strategies for drill site selection**

The strategy for drill site selection is mainly dependent on the drilling objectives. Key questions posed are: Where is it possible to drill the targeted strata? What resolution should be obtained? Is it critical to have a continuous sequence? May it be an option to drill the targeted strata at shallower depth with an incomplete or condensed sequence above?

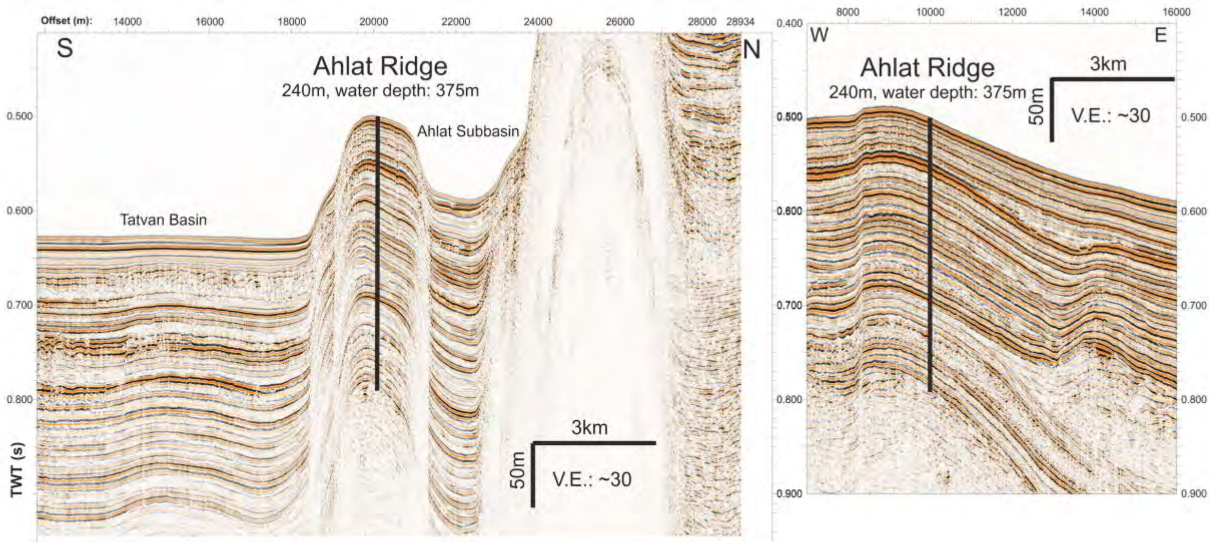


*Fig. 4.1.13: Crossing high-resolution seismic profiles at a suggested drill sites in Lake Van, Turkey, in which only a combined interpretation of both profiles allows understanding the structural context of the suggested site, modified after Litt et al. (2009) and Cukur et al. (2014)*

One always has to keep in mind that seismic profiles are a 2D-image of the 3D-subsurface. Hence, it is highly recommended to have crossing profiles at potential drill sites or a grid of seismic profiles, which allows extracting the 3D-subsurface from 2D seismic profiles (Fig. 4.1.13). During drill site selection, the option of constructing composite sites should also be kept in mind. It may well be that a complete sedimentary succession may not be drilled at one site but that it is necessary to construct such a section from several sites. An educated combined selection of sites may allow reaching a long record by drilling several relatively shallow sites instead of one very deep site (Fig. 4.1.14)

A major challenge is defining the drilling depth. Seismic data are recorded in two-way traveltime, while drilling contractors and funding agencies expect drilling depths in meters or feet. The sound velocity of the lithologies penetrated is needed to convert two-way traveltime in depths, but reliable sound velocities are often not available. Hence, a drilling project proponent has to assume specific sound velocities. Shallow water-saturated lake sediments have velocities close to the sound velocity of water and 1600 m/s is usually a good value for doing the conversion. However, individual layers (e.g. thick tephra layers) may have much higher sound velocities leading to an underestimation of the desired drilling depth. Higher velocities must also be used for compacted sediments at depth or igneous rocks but estimates can be only vague before drilling. In addition, it is of greatest interest to assess the deposition age geological time of the sediments. Accordingly, sedimentation rates have to be anticipated as well. One approach is to use sedimentation rates obtained from shallow cores. This is - of course - oversimplified but very often the only option. Seismic data may also be used to develop an age model (e.g. by distinguishing between glacial and interglacial deposits, Lindhorst et al., 2015) but this approach has again large uncertainties. Therefore, estimating the geological time of a record to be drilled is often not more than an educated guess.

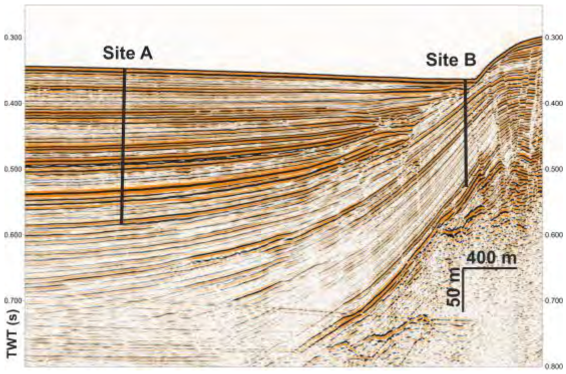


*Fig. 4.1.14: Drilling at site A allows to recover a complete section of undisturbed sediments. Instead of deepening site A, older sediments can be drilled at site B at much lesser drilling depth. Modified after Wagner et al. (2014).*

**SAFETY, HEALTH, PERMITTING**

Safety and health at a drill site and for the crew are of paramount importance in a drilling project. Accordingly, not only the scientific objectives and geological conditions will govern the selection of a drill site, but also safety must be a leading criterion. First of all, geological and geophysical site knowledge of potential hazards that may affect a drill site is critical. Central matters are:

- Hydrocarbon occurrences
- Shallow gas
- Gas hydrates
- Fluid (over)pressures
- Borehole instabilities, stress, strain
- Salt, clay or other rocks affecting drilling
- Variable hydraulic conditions
- Well site, slope instability

Before drilling can start or applications for permits can be submitted, it must be either excluded that hydrocarbons, over-pressured fluids, $H_2S$, magma and very unstable zones will be encountered or that the technical planning will include measures to handle such issues in a way that the environment is not endangered and/or drill-site safety is compromised.

Depending on the permitting authorities and national laws, pre-site surveys may include environmental impact studies, which must cover additional safety and health-related necessities and be obtained and/or conducted in advance to any drilling operation.

For permitting procedures, a safety or drilling-hazard report is usually required. Key elements for composing such reports are not only the drilling procedures (see the following chapter) but often also the site survey data. Since consequences and costs of drilling hazards are in most cases extensive, every effort must be made to minimize the risk. Drilling contractor, lead scientists as well as permitting authorities have to work closely together to achieve this goal. Accordingly, before concrete pre-site survey work it is time to invest in the permitting procedures and to communicate with all relevant authorities. If, for example, permissions for seismic investigations are needed, it is a good time to evaluate conditions for drilling permissions.

PIs and project managers should be aware that lack of timely drilling permissions is one of the major causes of delays in ICDP projects.

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CHAPTER 4.2

# Drilling Operations and Engineering

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Drilling operations are highly professional tasks requiring special expertise and skills. Therefore, Principal Investigators (PIs) usually contract service companies to plan and execute scientific drilling. Accordingly, the PIs have the duty to oversee all operations as well as to control schedules and budget. In several projects supported by ICDP, these PIs´ tasks have been either entrusted to independent drilling consultants or to the OSG engineers. They performed as technical and managerial advisors or 'company men' at the drilling site and were supported by additional external experts when needed. This system allows PIs to focus on oversight issues and information to stakeholders and scientific community. In order to describe the operational and engineering tasks, this chapter summarizes some key aspects of drilling engineering and operations execution.

**Basics of drilling**

In the majority of drilling operations for scientific goals either rotary drilling or diamond wireline coring techniques have been used. In both cases a bit is mounted on a rotating steel pipe and lowered into the ground by a drilling derrick (Fig. 4.2.1). For deep drilling operations, bottom hole assemblies made up of a bit, stabilizers, reamers, drill collars and heavy weight drill pipe are needed. The drill string is propelled by a rotary table, or a top-drive, and consists of connected pipe elements through which a drilling fluid is pumped down the well. The drill mud, usually water with clay minerals and some other minor additives to adjust density, viscosity and lubrication, cools the bit and carries cuttings of the destroyed volume of rock to the surface through the annulus between the borehole wall and the drill-string. Modern oilfield type drilling uses downhole motors that are propelled by the drill mud. The circulating drilling fluid is treated at surface to remove the solids and control the 'mud' properties. The drilling progress (rate of penetration, ROP) is controlled by rotary speed, weight-on-bit (WOP), and mud hydraulics. Once a drill pipe length is completely drilled down, an additional pipe is connected to extend the drill string.

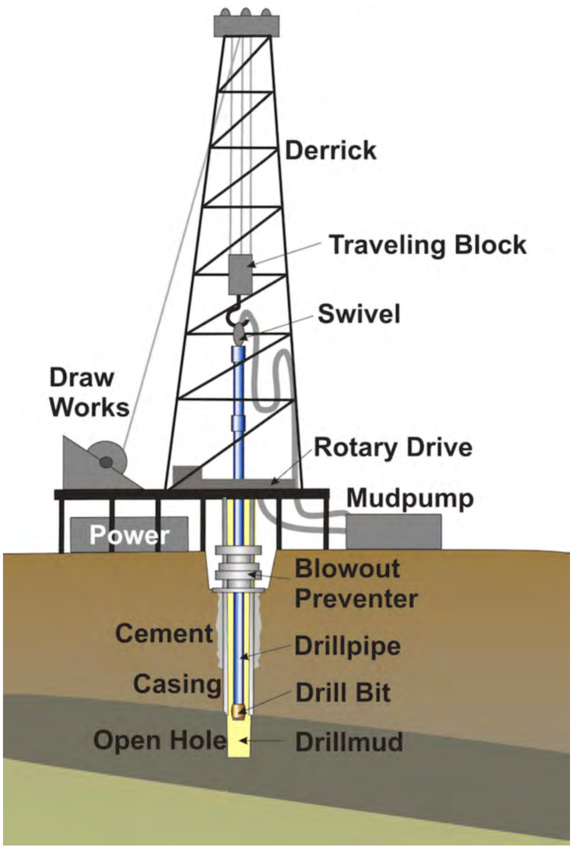


*Fig. 4.2.1: Key components of rotary drilling*

When drilling from a ship or floating platform, the borehole remains open to the sea/lake floor, so mud and cuttings do not return to the drill rig. In this set-up drilling must be performed with water in place of drilling mud allowing cuttings spilling out on sea or lake bottom around the well. However, if pressure control and mud return is required, an outer second pipe, a so-called riser, is put in place so the mud and cuttings can be pumped back to the deck.

Coring is performed with a hollow core bit that leaves a central column of rock. This core slides into a pipe barrel while drilling progresses. In the oilfield rotary coring technique, after coring the length of the core barrel, the whole assembly has to be pulled back out of the hole (pipe trip out) to get the core to the surface. In many scientific drilling projects, by contrast, continuous coring by wireline coring technique is utilized to avoid time-consuming round trips. The core barrel is retrieved through the drill string by sinking a wireline catching device that connects to the retrievable inner coring assembly with the drilled-out rock column inside. Once latched into the coring assembly's head, the core barrel is winched up to surface and replaced by an empty core barrel for the next round.

The actual formation-cutting method varies depending on the type of rock or sediment present along depth. Typically, thin-kerf diamond core bits with high-rotation speed are used for hard rock drilling, roller cone abrasion bits are used for softer sedimentary rock, and non-rotating sharp edged hollow metal pistons of several meters length are hydraulically shot (forced) into soft sea/lake-floor sediments to collect cores and thus advance the borehole.

Instable borehole conditions as well as saline or over-pressured formations often require that casing or liner pipes have to be installed. To hold casing in place and avoid formation fluid migration to surface, the casing must be cemented in place after being run in hole. Usually, wells are drilled following a telescopic configuration, starting with largest hole diameter at surface and ending up in the smallest diameter at bottom hole. Exceptions are so-called monobore configurations with static diameter from surface to end depth. Health, safety and environmental regulations or critical downhole conditions often require additional procedures to ensure safe drilling operations and to minimize environmental impact. This includes borehole stability control through mud density variation, biodegradable drilling fluid additives and blowout-preventers (BOP) devices.

**Wireline coring**

Exploration or diamond core drilling is used in the mining industry to probe rock formations in search of mineral resources. A thin-kerfed diamond core bit is rotated by slim drilling rods at high speeds. The core barrel is retrieved via wireline to the surface. The technique has been widely adapted in scientific drilling because of the capability of continuous coring without having to pull the drill pipe out of the hole. In addition, the slim diameters utilized allow minimizing the rock volume drilled and hence reducing costs. At the same time, the disadvantages of this method are the small core diameters and limitations to achieve enhanced drilling and coring depths.

**Standard Diamond Coring Sizes**

| Type | Hole Size | Core OD |
|---|---|---|
| **PQ** | 123 mm | 83/85 mm |
| **HQ** | 96 mm | 61/63.5 mm |
| **NQ** | 76 mm | 48 mm |

*Tab. 4.2.1: Standard Diamond Coring sizes for hard-rock coring operations, OD= outer diameter*

*Fig. 4.2.2: Truck-mounted wireline coring rig at Snake River Plain (Project HOTSPOT)*

In several shallow to medium deep ICDP projects, diamond wireline coring has been utilized very successfully. For example, in the Snake River Plain HOTSPOT project in Idaho, USA, three almost 2000 m deep wells were drilled with this technique. A wireline coring rig (Fig. 4.2.2) was used that can deploy 1000 m of PQ, 1500 m HQ or 2500 NQ drill string.

Following the telescopic well architecture, drilling starts with the larger size diameter from surface and continues as long as possible until the formation in the open hole has to be stabilized with permanent or provisional liners or casings. The next smaller size drill pipe has to be used to continue coring and needed to line or case the hole with the corresponding casing size.

**Combined techniques**

Wireline diamond coring has also been utilized with oilfield drilling rigs deploying a hybrid coring system. ICDPs Chicxulub Drilling Project started with cementing an 8 m deep conductor casing. A section of Tertiary limestones (392 m depth) was penetrated without coring by standard rotary drilling (312 mm diameter), cased (245 mm) and cemented (Fig. 4.2.3). The following two sections were continuously cored with a HQ string to about 1000 m depth until the pipe got stuck. The subsequent NQ section was deepened to 1510 m and left open.

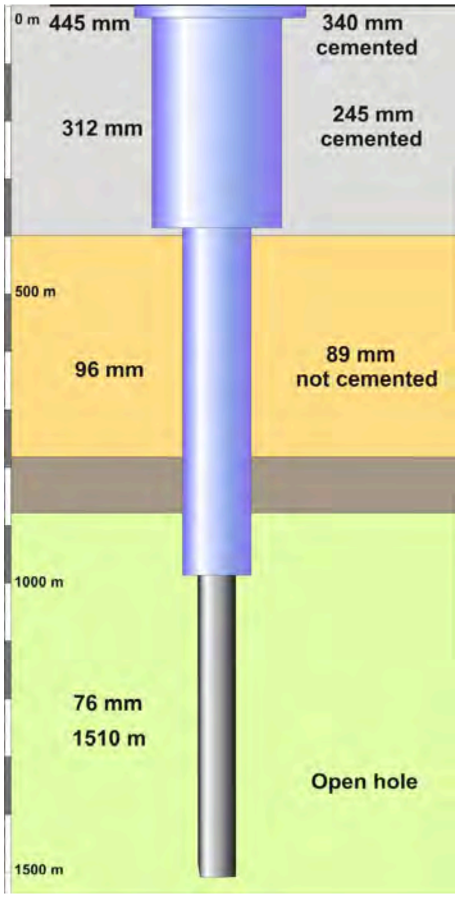


*Fig. 4.2.3: Sketch of ICDP Chicxulub well with hole size on the left and casing diameter of the right*

**Lake sediment drilling**

Undisturbed, lacustrine sediment cores serve as important archives for high-resolution studies in environmentally sensitive areas. One of the major issues in sampling those archives is the lack of suitable and cost-effective sampling tools. A very successful approach has been achieved through the redesign of available wireline drilling technology. The Global Lake Drilling unit GLAD800 and its successor, the Deep Lake Drilling System (DLDS) were owned by ICDP and operated by a service contractor. The major components are:

- a wireline drilling rig (Atlas Copco T3W DH)
- four-motor rotary top-head drive
- a container-size modular and versatile barge (24.4 x 7.3 m, Damen system)
- anchor winches or dynamic positioning systems, mud tank, crane and other auxiliary equipment

*Fig. 4.2.4: DLDS on Dead Sea*

The diamond wireline drilling technique utilizes various special coring tools and can reach depths up to 1400 m depth (CHD 134 string) in 400 m water depth. The DLDS is a complex and modern drilling unit, which requires a crew of experienced, well-trained technicians and engineers for drilling and marine operations on a 24/7 basis (Fig. 4.2.4).

The GLAD800 was deployed with ICDP funding in Lakes Titicaca, Bosumtwi, Peten Itza and as an arctic version on the frozen Lake Elgygytgyn. When severe weather hampered GLAD800 operations significantly during Lake Qinghai and Laguna Potrok Aike operations, a new barge system was designed and built as Deep Lake Drilling System DLDS by DOSECC. The new DLDS was subsequently deployed thereafter in deep-drilling ICDP projects on Lake Van, the Dead Sea and Lake Towuti. The rig was also used in the offshore Chicxulub Crater Drilling Project.

During the Lake Ohrid drilling expedition of ICDP in Macedonia using the DLDS, 480 m coring depth was reached twice within less than 17 days of drilling time, with core recovery rates of over 90% per site. There is hence no doubt that this is a very capable barge drilling system. Nevertheless, it is also limited to wave heights < 1 m and wind speeds of less than 4 Beaufort. Furthermore, mobilization and demobilization are cost-intensive as it comes in 14 20-ft-long shipping containers. Furthermore, staging the barge into water requires a 100-t-crane and a rigid quayside or slipway. Site location, available local infrastructure and logistics constraints can further complicate deployment of lake drilling systemy. Safety and hazard considerations for and around the entire operation must be specified in detail as part of the science and operations plan along the planning phase of the project management strategy.

**Soft sediment coring**

Loose and soft sandy to clay-rich sediments are not easy to probe continuously. First, all coring devices may lose the lowermost core section from the so-called core-catcher during each coring run. Therefore, to ensure complete core coverage it is necessary to deploy these systems at two or three parallel holes per site, which allows a data processing called 'splicing' (aka: depth-matching of geological horizons across boreholes, see Chapter Core Handling). Second, there is no coring device that is capable of recovering the uppermost water-rich and very unconsolidated sediments at the same recovery percentage as deeper consolidated sections. Accordingly, different coring tools for different lithologies are needed.

A set of coring devices is used to collect different types of lake sediment (Fig. 4.2.5). The distinctive kits are deployed via wireline through standard drilling assemblies yielding a 139.7 mm (5.5´´) hole:

- Hydraulic Advanced Piston Corer (APC)
- Extended shoe, non-rotating (EXN)
- Extended core bit, rotating (XCB)
- Diamond core bit (mining)
- Non-coring assembly using rotary bit

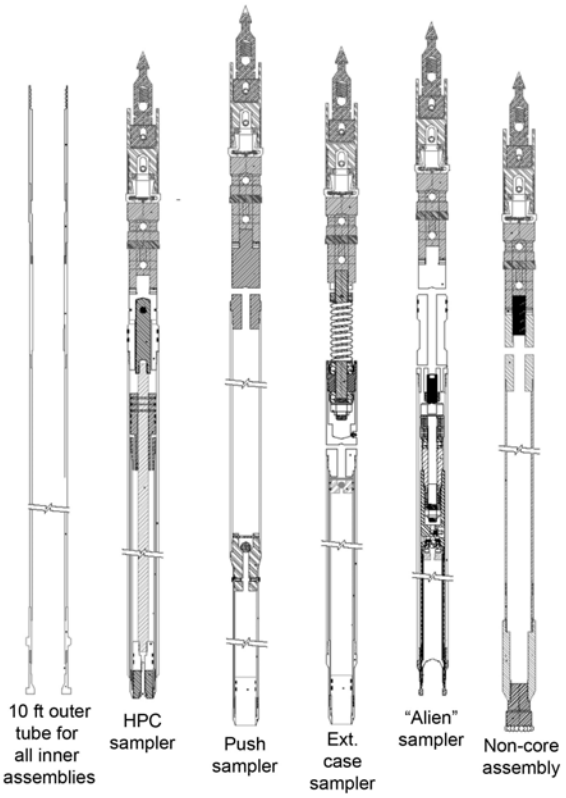


*Fig. 4.2.5: Tools used for coring lake sediments*

The APC device produces by far the best recovery rate - often near 100% - and delivers the most intact, neat, undisturbed samples. This APC method has been developed in the international ocean drilling programs. It works through mud pressure built-up on a metal tube ending in a tapered sharp cutting shoe that penetrates the substrate. The tool is activated when the shear pins break once a precalculated pump pressure is reached, driving the core tube into sediments, usually in 3 m steps (note: 9.5 meters of advancement for IODP drilling operations). After each shot the core barrel containing the inner plastic liner is retrieved by wireline through the drill string to surface. On deck, the inner plastic liner with the sediment section is retrieved from the core barrel. For the next run, the barrel is loaded with a liner and shear pins at surface then it is dropped back through the drill string for the next shot. The HPC/APC tools deployment is abandoned once coring progress is obstructed in strong compacted or coarse-grained deposits.

The most appropriate next coring tools are either the non-rotating extended nose (EXN), or the rotating extended core bit (XCB) - also called 'alien tool', which consists of an inner core bit preceding the outer rotating main bit. In this way the progressing well deepening is separated from the core cutting process. It allows for reaching greater coring depths, but usually results in a slightly lesser degree of core recovery.

**Drilling engineering**

Professional planning and drilling engineering need to be performed for all deep and complex drilling operations. Examples of complex planning and engineering are provided in the following paragraphs. The OSG can provide assistance for ICDP projects in drilling engineering. Experts and consultants in drilling engineering usually prepare the complete well planning using modern software packages. The software in general is organized in modules or components that describe the well life cycle and planning phases (Fig. 4. 2.6).

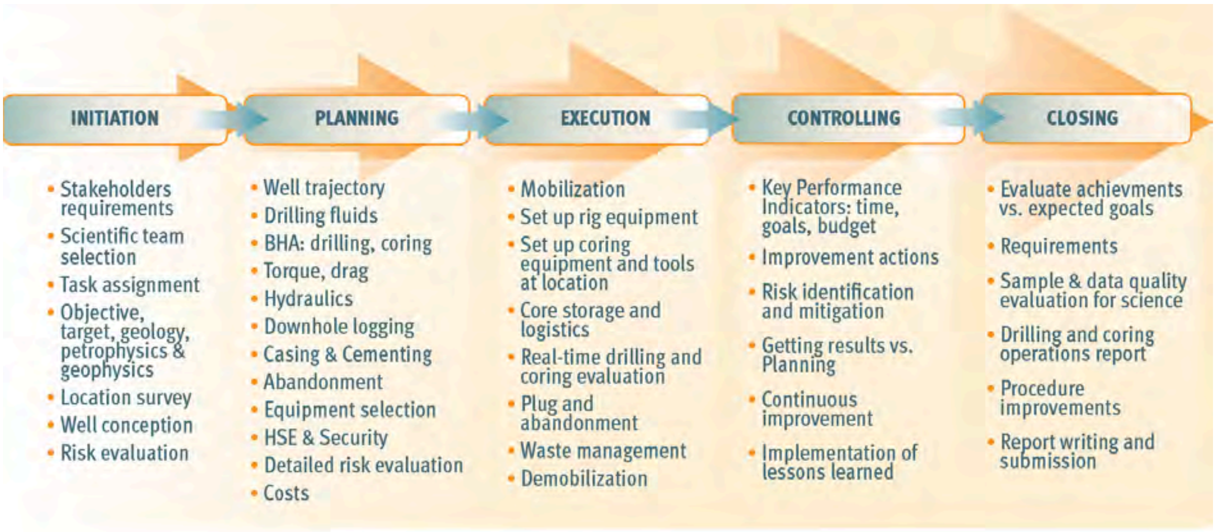


Fig. 4.2.6: Planning phases and well life cycle

These well planning software solutions are most often delivered as single, unified applications with integrated multiple software components. A description of the modules associated with the planning steps to plan a well is provided in the following paragraphs.

**Geology and geophysics module**

Modern Geology and Geophysics software for drilling planning takes subsurface information to generate geological knowledge and parameters out of these diverse data sources. The power of today's advanced computers, combined with broad data integration, allows geologists to apply many methods and technologies to evaluate their science data (Figs. 4.2.7 and 4.2.8). The final goal is to achieve a geologically consistent base for a thorough engineering project planning process.

These processes can be evaluated and qualified for the uncertainties that are inherent in both the input data and the variability of geology. The full capability of today's advanced geological interpretation and modelling software is generally defined by a few distinct functionalities:

- The efficient and thorough processing and interpretation of borehole measurements for optimal formation evaluation
- Advanced modelling tools used to construct structural and stratigraphic models, in order to validate and refine the geologic interpretation utilizing digital structural analysis tools
- The capacity to handle any amount of complex faults, under avoidance of simplifications
- Application of multiple geostatistical methods in order to assess and mitigate data uncertainties, and
- A seamless integration with seismic, oil field production and other data sources that enrich geological workflows, towards a direct process for generating geo-cellular simulation grids

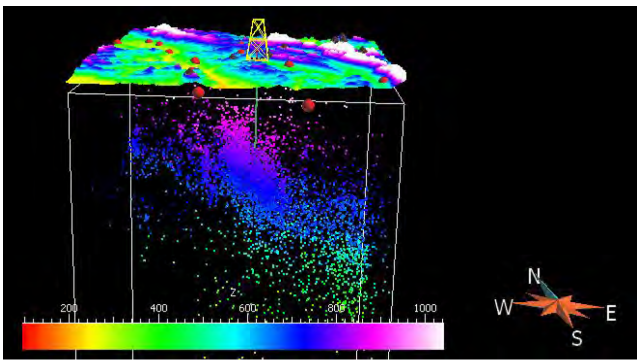


*Fig. 4.2.7: 3D attribute integration in a model*

When a project starts, the initial data screening will evaluate geologic formations and petrophysics of the projected subsurface area. In the project definition phase, the basic questions that a geologist will initially be challenged with are, for example, facies classification, borehole image interpretation from offset wells, lithological core interpretation and saturation determination.

In order to build the 3D geologic model, correlation and building of geologic cross sections will initially have to be performed. Interpreted well sections will be constructed from wireline logs that carry the data needed to perform stratigraphic correlation, while seismic data may also be incorporated at this stage. The G&G software then constructs net thickness maps while markers are interpreted and geologic zones of research interest identified. Stratigraphic information created during this interpretation phase is then directly used for the construction of the 3D stratigraphic model.

Modern software suites will construct structural 3D models automatically based on the stratigraphic column, as well as on interpreted faults and salt body structures. They are capable of defining fault-fault and fault-salt contacts automatically, and they can build horizons following the rules of sequence stratigraphy.

Horizons and faults will be identified by the software in order to create and suggest a sealed model that can be used later to generate consistent maps, velocity models, geological and flow simulation grids. An advanced 3D model should have none of the limitations of pillar-based models. It should be able to handle any kind of faulting, and can therefore efficiently represent any stratigraphy between horizons.

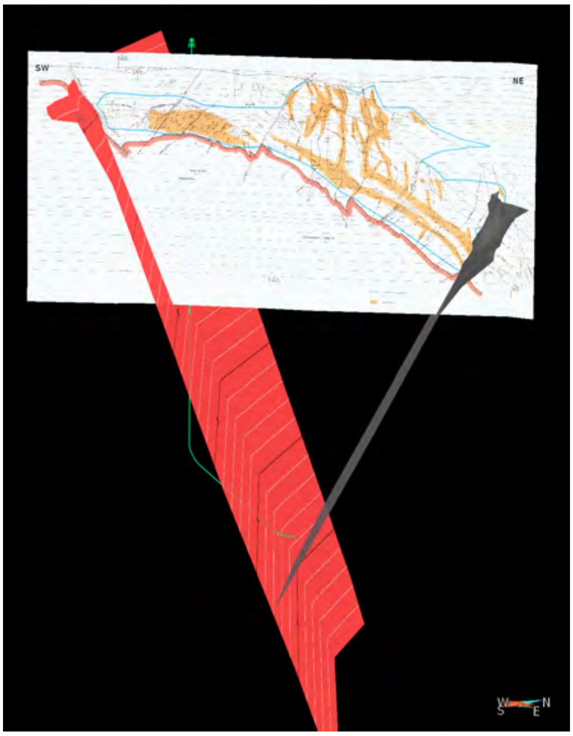

*Fig. 4.2.8: Fault (red, grey) visualization in geologic section with well path (green) of Schneeberg-1 research well (courtesy: LfULG, State of Saxony)*

The 3D geologic model contains further information about the paleo-geographic coordinates of all the cells of the geologic grid created inside the 3D model. Geostatistical algorithms may then be run inside the paleo-space in order to undo post-deposition deformation.

By applying a dynamic uncertainty-considerate workflow, the user can construct, based on this analysis, a reservoir property model by first performing a facies distribution per each layer, using a complete set of categorical simulation algorithms. For each facia, it should be possible to populate all the petrophysical parameters needed using kriging (statistical) or simulation methods.

As data uncertainty always heavily hampers or influences geological interpretation due to sparse information and being very interpretative, a uniform approach to uncertainties in petrophysics, structure and properties is therefore required. Uncertainty is not only present in the algorithm that the modeller chooses to apply; it is also present in all the parameters and the data used in those algorithms. Uncertainty about correlation coefficients, variogram range, or with porosity distributions requires a sensitivity analysis of all modelling input parameters. When dealing with uncertainty, the most important factor is to know which parameters govern and dominate a geological setting or model, so that the workflow can be optimized and steps can be taken to reduce this uncertainty. Integrated G&G software suites can help and guide the user in this process to substantially reduce model uncertainty.

The ultimate output resulting from a G&G software is the mathematical transform from static to dynamic models. The 3D model may be discretized to automatically construct a flow simulation grid, where all necessary faults are taken into account and all cell geometries are optimized for a high-performance flow simulation. Up-scaling between the fine-scale geologic grid and the coarser flow simulation grid should assure spatial integrity.

As the final step in modelling, the reservoir flow simulation grid can now be constructed in any geological setting for reservoir simulation and a so-called history matching. This includes fault geometry or fault inclusion in the flow simulation model by incorporating all faults, which are needed to perform an acceptable history matching. This is crucial and critical in all reservoir characterization tasks.

Most of the software application suites are built atop of a multi-user, multi-site and multi-OS data management platform. All modelling processes are encapsulated inside workflow management guides to also assist the occasional user, as well as to store all the parameters used to construct a model for audit ability and QC purposes.

Special attention should be given to the fact that all software applications are open, allowing outside vendors to add proprietary or third-party technologies as added on software solutions. This can involve plugins that have full access to other data models or an open framework for a fast prototyping environment that allows developers to creating new commands into the 3D visualization window and dialog boxes, and insert them into existing menus. Some G&G solutions even offer a high-level programming language to add new algorithms and processes directly within the user interface.

**Well planning and management module**

A well planning package is used to plan trajectories of new wells or side-tracks, multilaterals, and re-entry from existing wells. The trajectories simulations start from existing wellbore information and trajectories stored in the common database (Fig. 4.2.9). All critical well information, like local boundaries, lease lines, casing sizes, borehole sections, comments and survey tools error margins can be defined and visualized at this stage of the planning process.

Engineers usually start the well planning process with the collection of topographical field information, e.g., available GIS data and the global position of fields, sites and borehole locations in geographic coordinates (Fig. 6.8). On the computer screen the planner visualizes and identifies targets, including their shape, dimension, thickness, rotation, dip and offset in that planning stage.

Geological surfaces and faults can also be incorporated at this stage for visualization, and intersections by the simulated well trajectory computed and displayed. The well planning software runs using a common database for all wellbore data, including mechanical, directional, geophysical, petrophysical and geologic field and well information.


*Fig. 4.2.9: Horizontal well trajectory for the Campi Flegrei deep drilling project in Italy*

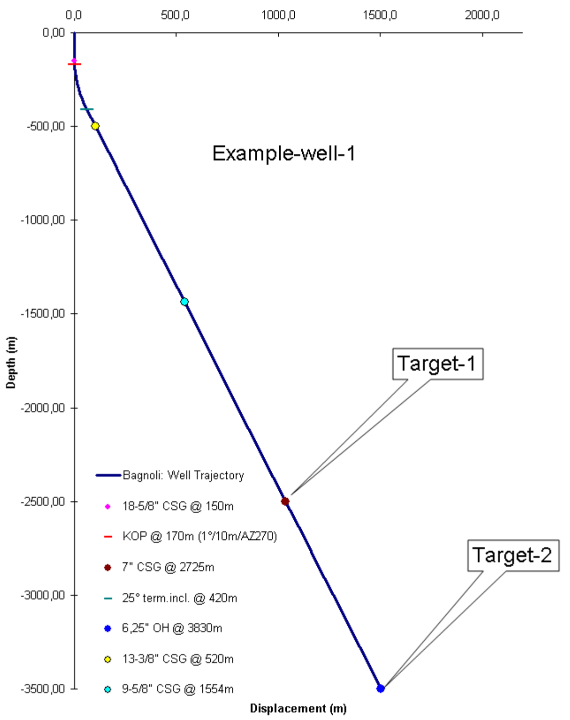


*Fig. 4.2.10: Directional well plan for Campi Flegrei project in Italy*

In reference to wellbore position uncertainty, the planning engineer in charge of designing the well trajectory has a full range of modelling techniques at hand for evaluating the different magnetic and gyroscopic survey data of the bore. This allows him to define the critical confidence level of calculated borehole subsurface coordinates for the present position of the borehole. Cones of uncertainty typically represent these confidence areas, as they need to be determined after Wolff and de Wardt, in SCWSA magnetic models, or in the manufacturer's gyro models (Fig. 4.2.11).

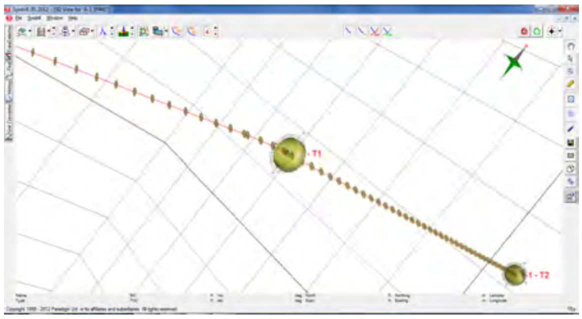

*Fig. 4.2.11: 3D view of uncertainties ellipses of planned Monte Civitello well in Umbria/Italy*

In addition, many packages do allow creating user-defined error models based on survey instrument manufacturer specification data. These position uncertainty models are particularly helpful in crowded borehole areas as they furnish an anti-collision analysis from the drilled and the neighbouring boreholes against offset wells stored in a common database. In this way a collision of new drilling wells with existing wells is avoided during directional or vertical drilling and a safe distance between wells is always kept. Results of this analysis typically include wellbore separation, ellipse separation, clearance factor and diverging depth ranges. The results are displayed in the form of ladder plots, a travelling cylinder or tabular formats, and accordingly highlight high, medium and low collision risks with a traffic light indicator.

For survey management, all recorded directional survey data during drilling or from logging runs, including overlapping surveys, are entered and stored in the systems database. The definitive wellbore is finally created by specifying proximity calculation and travelling cylinder plots. 3D views to/from depths for each survey section can be performed in order to eventually decide on a definitive and wellbore position and its final positional uncertainty. Once the final survey has been loaded, it is locked, thus ensuring the integrity of the database for anti-collision analysis or future side-tracks and new well drillings thereafter.

When the drilling is underway, a current drilling on real-time trend feed from measuring- and logging-while-drilling tools (MWD, LWD) can be analysed with the so-called project–ahead functionality in order to determine whether drilling corrective action on course is needed. If a correction is required, a revised trajectory is usually calculated by the drilling engineer based upon one of the selected modes ‘return to plan’, ‘nudge/steer or ‘project to target’ definitions. Projections, including positional uncertainty, are at this stage visualized in 3D viewers and can be compared to the drillers’ target or the earth model from the G&G suite for clarity and decision-taking purposes. All projections at this stage should be saved for quality-control (QC) purposes for later engineering analysis and decision-taking on the rig.

Ideally, the deepening progress of the actual wellbore can be interactively monitored in the 3D viewer and continuously compared to the planned wellbore and other wells in the vicinity. Thus, geological surfaces, casings, positions of uncertainty and drillers’ targets are incorporated in the 3D viewer. The data should be written in electronic HTML format, allowing interactive viewing in a standard Web browser by other groups of researchers who can then remotely log into the database. All visualisations and calculations ought to be documented by an advanced well-planning software package through an extensive set of pre-defined plot and report templates. Users should be able to define plots and reports that can be saved and their settings later re-used. Customizable plan section, travelling cylinder, 3D and survey comparison plots should be standard by the majority of the advanced drilling planning software tools.

**Bottom-Hole-Assembly Design**

One of the first steps in drilling engineering is to validate the selected well trajectory by analysing the well bore profile mechanically and dynamically including the Bottom Hole Assembly (BHA). This helps to ensure that the drilling can actually achieve its objectives without drill string failure, injuries to people and loss of rig time. For this task the Torque (TQ) & Drag optimization and analysis software package is typically used by the drilling planning engineer in order to model all types of Bottom-Hole drilling Assemblies (BHA), casing and completion strings with respect to their suitability (Fig 4.2.12). This design phase provides a clear overview of the mechanical performance of the tools and the suitable wellbore trajectory and geometry, which will influence project budget. A pick & choose BHA string constructor is embedded in these engineering packages allowing complex BHA’s to be quickly constructed by rapidly filtering through and selecting from extensive catalogues of industry supplied drilling equipment. The PIs should always consider the complexity of the calculation made by the engineer to take decisions or make suggestions to optimize resources while keeping high performance and quality. The software allows the engineer to create virtual simulations of using different tools and geosteering technologies and find the most suitable application targeting performance and cost.

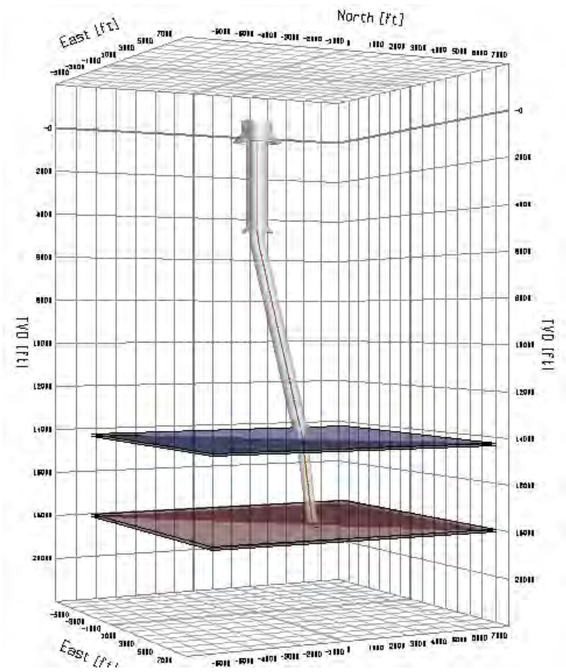


*Fig. 4.2.12: Casing scheme with 3D well profile and geologic targets in Monte Civitello project in Italy*

Often a customizable material selector user interface allows new grades of steel to be incorporated into the drill assembly. The functionality of API (American Petroleum Institute) rotary shouldered drill pipe as well as the most common API casing connections should be pre-loaded in the software, which is capable of being individually extended by the user. This allows the calculation of connection thread properties and connection strength of customized thread connections. BHAs that have been created in past projects preserve selected catalogues for future re-use, as well as new industry catalogues, which can be added upon availability. The planning engineer should be able to generate a customizable graphical view in order to combine mechanical properties and physical dimension plots.

BHAs must not only be analysed for their mechanical suitability, but as well for predicting their directional behaviour. Soft -& stiff string analysis options allow calculating all forces acting upon the BHA during the drilling process, including torque, drag, stresses and side forces (Fig. 4.2.13). The calculated loads are compared to buckling, string yield and rig operating limits, and the results presented to the drilling engineer using a ‘traffic light’ approach for quick identification of potentially hazardous drilling conditions.

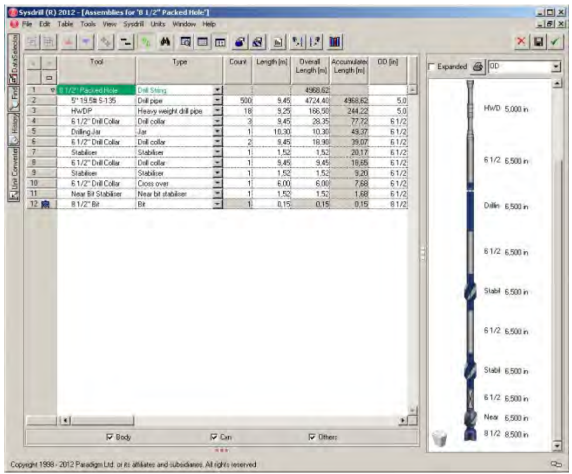

*Fig. 4.2.13: BHA builder with Sysdrill well planning and engineering software suite*

User-defined operating modes, like reaming, sliding, steering or rotary can be incorporated in the calculation, allowing forward-modelling of the drilling process and generated loads for a given hole-section. In relation to directional prediction of BHAs, a range calculation performs a full drilling dynamic analysis at varying depth and provides a summary of surface results. Hook load and surface torque readings gained from the rig site are entered and displayed in such range graphs. This allows comparing modelled with observed loads during drilling.

The modelling and analysis of axial and torsional friction factor conditions and reduction effects from special torque-reducing drilling tools is a further important output of a TQ & Drag engineering package. Initial friction factors will be obtained from industry reports or by using well data from previously drilled wells. While drilling the well, friction factors are back-calculated, allowing realistic analysis and prediction for sections ahead and future wells in the area to come. By including hydraulic effects, the additional viscous forces and pressure induced stresses can be further included in this advanced analysis.

One of the most valued products of real-time drilling dynamics is the stuck-pipe calculator, which is used to predict a potential stuck point depth during the drilling process. Its analysis is based on measured surface torque, pipe twist, and surface over pull and stretch, taking into consideration hole inclination friction factors and borehole stability conditions. Modelling results are typically presented in traffic light display for ease of reaction to upcoming hazards.

Another important output of the TQ & Drag package is the critical rotary speed analysis. It predicts the rotational speeds at which resonant frequencies may develop. This analysis is taking into account axial, lateral and torsional vibration modes, and highlights rotary speeds to increase chances of avoiding and preventing excessive string damage and BHA failure during drilling.

**Drilling hydraulics**

The aim of a hydraulics optimization and analysis package is to model downhole circulating pressures during drilling, tripping and running casing in order to enhance bit hydraulic performance and ensure effective hole-cleaning as well as bit cutter cooling.

Basis for hydraulic engineering is the rheology model selection, a software-supported fluid builder device, which allows accurate definition of fluid properties for use in all subsequent hydraulic engineering calculations.

Properties of selected drilling fluids are typically stored in catalogues for re-use in other analysis models. A rheology modelling tool, for example, can analyse drilling fluids and automatically selects the most suitable rheology model based upon viscometer readings. Power Law, Bingham Plastic, Herschel Bulkley & Robertson Stiff models are supported by most hydraulic packages.

Swab/surge and equivalent circulating density (ECD) analysis are performed to reduce the risk of formation breakdown or swab-induced influxes during tripping operation and drilling. Drill string geometries and cuttings concentration in the mud column are equally considered in the ECD calculation for defining the operable mud window. Cuttings transport ratio and annular critical velocities are additional outputs of the model.

Most hydraulic software packages feature a fluid temperature modelling functionality, which provides a quasi-steady state temperature model, incorporating an advanced compositional density and HPHT rheology model. This allows to simulating a number of drilling scenarios, i.e. complex geothermal gradients, horizontal wells and dual-gradient mud systems. This functionality is, in particular, required for an accurate prediction of ECDs, and equivalent downhole mud density as well as rheology under high-pressure, high-temperature (HP/HT) conditions.

As an output, the hydraulic software package includes several modes of optimization, including pump pressure, flow rate, % bit pressure loss and bit total flow area (TFA) calculations. Bottom hole horsepower curves can be generated, showing hydraulic power and impact force with varying flow rate and bit TFA. Nozzle configuration and TFA can be calculated depending on flow rate and surface pressure conditions, thus enhancing and optimizing the bottom hole hydraulic energy for maximized rate of penetration (ROP). Other responses and feedback mechanisms from a hydraulic software package are the calculation of the maximum running speed for BHA's and casing strings (with both open and closed pipe) in order to avoid borehole damage due to surge and swab pressure effects.

For the selection of most efficient parameters, a sensitivity analysis allows the calculation of all pressure limits and tolerable ECDs at varying flow rates, indicating minimum and maximum flow rates.

**Casing and tubing analysis**
A modern casing design package allows the drilling engineer to design the minimum number of casing strings required to safely complete a well, thereby maximizing drilling efficiency and optimizing well capital cost (Fig. 4.2.14).

For each casing selection, the casing setting depths are automatically calculated in the casing analysis package based upon pressure data and user-defined constraints such as trip margin, kick tolerance and maximum open-hole distance.

The design procedure of a casing string and its strength analysis should include: 1) uni-axial, half bi-axial, full bi-axial and tri-axial stress checks for axial load cases; 2) bust and collapse load cases for all stages of the well's life cycle, including all drilling phases with their changing mud properties or pressure imbalances; the latter includes well-kicks or mud losses and the analysis of the well production phase after drilling under different temperature and pressure conditions; 3) graphical plots, tabular data and traffic light pass/fail indicators should allow rapid identification of problematic loading conditions.

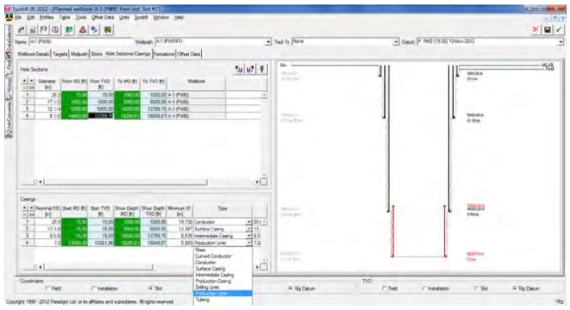

*Fig. 4.2.14: Casing design and calculation template from Sysdrill well planning & engineering suite.*

As casings do wear with time and with the deepening of the well due to the friction by the rotating drill string, a casing wear module should be applied to predict internal casing wear for a number of drilling operation and should be able to de-rate casing thickness for burst and collapse calculation accordingly. Alternatively, a calliper log can be incorporated as a percentage-wear identification measurement device and used to planning ahead the drilling process.

**Cementing engineering**
A cementing engineering and analysis module is used to plan cementing operations in order to ensure the safe slurry pumping schedule among casing strings and drilled hole, the annulus, or and cement plugs for directional drilling side tracks or plug and abandonment programs. It optimizes pumping operations for variable flow rate schedules, i.e., fixed flow rate, fixed bottom hole pressure, and free fall cement in order to safely manage down-hole pressures during such operations to avoid to fracture the

formation, underbalance the well, or either collapse or burst the casing. This software module most often stands as a back-up and Quality-Control (QC) check to service company proprietary cementing programs also to assure proper well integrity results.

An animated wellbore cementing analysis calculation allows monitoring of fluid flow regimes (lineal or turbulent), bottom hole pressures, ECDs, and flow rates as cement is circulated into position. Simultaneously, expected pump, choke and hydrostatic pressures and pressure losses are calculated. Bottom-hole pressures during cementing are plotted against formation fracture gradient and breakdown gradient in order to detect and prevent fracking and loss of fluids in the well. The cement volume calculator, which is available via the cementing or hydraulics software modules, will further provide solutions to many common well site volumetric problems, including pill spotting and balanced cement plugging.

**Downhole Pressures and Well Control**

Drilling across different formations and depths exposes staff and equipment at the rig site to unexpected downhole pressures and the corresponding fluids. Accordingly, pressures need to be properly controlled with pressure barriers and well control procedures. Along the development of the well planning and the acquisition of geological details, personnel in charge must analyse the potential of unexpected formation pressures carefully, especially when pressurized sedimentary formations will be truncated. Unexpected and uncontrolled downhole pressures and formation flows, commonly called kicks, could lead to blow out situations which can be disastrous and lead to complete project failure.

While drilling the well the first downhole pressure barrier is the drilling fluids specific weight or density. It serves to generate sufficient hydrostatic pressure values slightly higher (overbalanced) than the expected normal formation pressures. Once a well is drilled deeper with cased and cemented sections, it is necessary to identify the sensitive fracture depth interval. This is the transition zone between the casing shoe and the open hole section in the case of a kick occurring. A well control-kick tolerance calculator is used to verify that casing shoes are set and cemented securely at safe depths to avoid formation break-down due to increasing hydrostatic pressure. Such overpressure may occur during the cementing of the well or due to kick migration and gas pressure expansion while drilling. The software tools allow to simulate a kick of a given size and to determine the maximum allowable influx volume and pressure at the casing shoe to avoid formation damage.

With the software tools kill sheets will be produced, including dynamic maximum allowable surface pressure (MAASP), volumes, strokes and a pressure step down chart to safely control the well in emergency situations. Should, during drilling, the well show possible kick indicators such as increasing drilling fluid volume, gas in the mud circulating system, a sudden increase of the rate of penetration, torque and drag, or a flowing well while pumps are shut down , then the driller will position the BHA, activate the BOP rams, and shut down the well. In order to bring the well back under control and to resume operations safely drillers will follow API best practices and international well control procedures of drilling and completions operations.

The well control methods and procedures require that the rig pressure control system specifications (Blow Out Preventer, surface lines, manifold, manifold choke, tanks, separators, and flares) are predefined to withstand well pressure and temperature maximum parameters during operations and that the well control methods are pre-established during the well planning phase including the casing design parameters, cementing programs, and the drilling fluid program. For the execution phase the PIs together with the company man will coordinate and review assigned tasks of the established procedure. The experience of the 'Company Man' at the rig site is fundamental to lead efficient and safe operations during the decision-making process.

### Integrated workflows

Many well-planning and engineering software packages today offer a tight integration with other software applications, running on one data management infrastructure. Thereby a common data management environment is essential for multidisciplinary teams of geoscientists and drilling engineers who plan and monitor wells to ensure optimal wellbore design and drilling progress. In figure 4.2.15 such integrated workflow is depicted.

A two-way link with seismic interpretation applications could be integrated for interactive well-design and trajectory monitoring workflows in a 3D interpretation environment, which interconnects the well database into combined well-planning, engineering and geo-steering workflows.

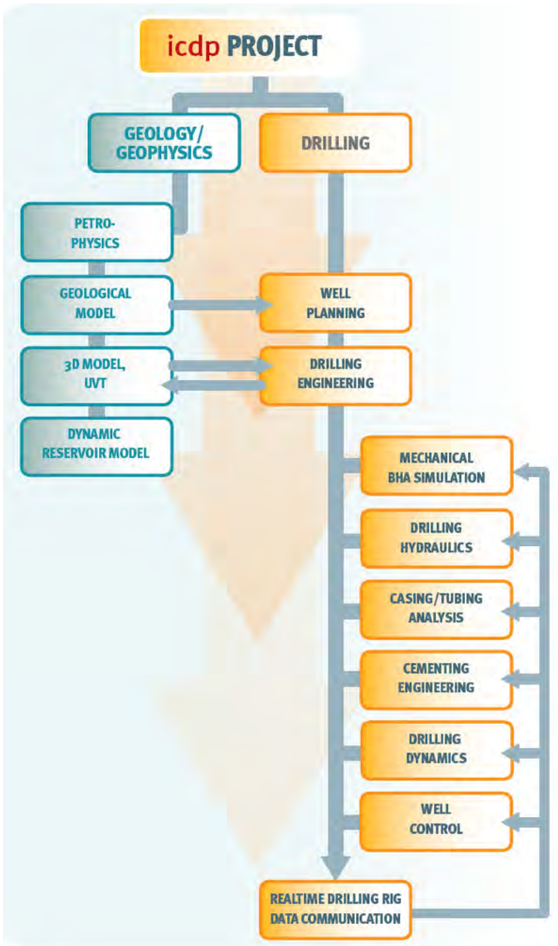


*Fig. 4.2.15: ICDP well engineering flow chart*

### Abandonment and Decommissioning

The final step of scientific drilling field operations is the proper management of well abandonment and surface facilities decommissioning to shut downfield operations.

Abandonment and decommissioning expenses including all capital and operational expenditures have to be accounted for early on in the project budget calculation. Scientific drilling projects often evolve during the operations when new open science question arise. This results in changing research objectives and more ambitious operational targets such as deeper wells using high-technology applications and long-term utilization of the well that may interfere with the budget set aside for well abandonment.

What has to be done with the well and surface facilities at the end of the drilling phase will depend to a large extent on governmental and local regulations. All surface facilities installed during drilling operations regularly need to be removed at the end of the project. The decommissioning plan must include the removal of all existing equipment or facilities from the drilling location. The removed equipment should be disposed by certified companies at qualified locations with supervision of accredited inspectors. Often, the location must be handed back to the landowner or state in the same (natural) conditions as at the time the project started. Accordingly, drilling site remedial and recultivation is an important and legally binding duty and liability.

Once all planned scientific on-site observations and measurements are done and related experiments and tests have been performed, the well needs to be plugged and abandoned. This is achieved by plugging open reservoir horizons and fresh water zones from bottom to surface. Reliable independent barriers are set downhole to avoid leakages or contamination by e.g., salty formation water or gas migration to freshwater zones or even to surface. From the engineering point of view plug and abandonment (P&A) means shutting down a well permanently to avoid influxes to the wellbore and surface. For this purpose, so-called bridge plugs of e.g., cement and viscous fluid pills are pumped into reservoir sections and wellbore to create reliable independent barriers. In this way contamination of aquifers or leakages from opened hydrocarbons reservoirs to surface and biosphere will be excluded. The individual length and position of the cement plugs has to be planned in accordance to legislation and in cooperation with permitting authorities to exclude any health, safety and environmental risk.

The UK and Norwegian national oil and gas P&A guidelines are recommended for guidance and can be applied in scientific drilling projects. Their program can be used for single or multiple well plugging and abandonment:

- Design or preparatory work: evaluate well integrity, identify well sections to be plugged, select equipment and skilled personnel, find out local liability and regulations
- Reservoir (horizons) abandonment: select and install primary and secondary barriers to test or produce from selected geological horizons or reservoirs
- Intermediate abandonment: select and install primary and secondary barriers towards upper flowing zones like aquifers or perforated horizons
- Wellhead and conductor casing cut and removal: cut casing and retrieve it and also remove the wellhead to proceed to cement the cellar

Designing the P&A job involves calculation of cementing pumping pressures combined with slurry densities and displacement fluids. In order to fulfill local regulations and warrant a safe working environment engineering consultant support will often be needed.

In many cases, as mentioned above, the natural preexisting vegetation has to be rehabilitated after the equipment and facilities deinstallation is completed. It may also be necessary to involve an environmental project supervisor for external inspection and audit. Local authorities or environmental agencies will need to evaluate the location to confirm that the original conditions are reestablished in conformity with local regulations. The surface facilities removing plan together with the P&A plan and the location environmental evaluation report shall be documented together in the Abandonment and Decommissioning Master Plan in order to hand it to the corresponding authorities.

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# Data Management

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Besides samples, data is one of the major products of a scientific drilling project. Data Management is therefore essential for both successful project completion and potential follow-up operations and publications. It is a long-term task that extends throughout the entire project and deserves a high level of attention from both the project management and the entire Science Team.

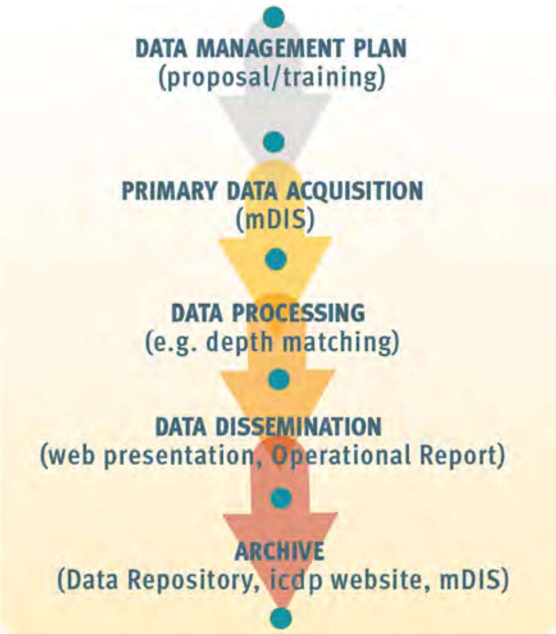


*Fig. 4.3.1: Data Management Lifecycle phases of an ICDP drilling project*

Ideally, all data gathered during the project forms a common basic data set (Operational Data Set), which is accessible for all Science Team members during the projects' drilling and sampling phases as well as for the whole science community at latest after the moratorium period. For that reason, ICDP provides the mobile Drilling Information System (mDIS), which is a database management application that ensures data integrity.

During the project lifetime Data Management is divided into five distinct phases, which are essential for any successful project and will be discussed in detail in this chapter and is shown in Fig. 4.4.1. The first phase is the development of the Data Management Plan (DMP), which should already be outlined in the Full Proposal. The second phase entails the primary data acquisition during drilling and laboratory operations. The third phase is the data processing, in which, for example, the measured core depth is matched with the depth gathered by geophysical logging measurements. The data gathered from the primary data acquisition and the data processing together form the Operational Data Set, which is in the fourth phase disseminated first to the science team and at latest after the moratorium period to the general public. The final data management phase comprises long-lasting activities such as archiving, ensuring that no data will be lost, and compiling key datasets produced by participants after the project ended.

**Phase 1: Data Management Plan**

The Data Management Plan, DMP should already be outlined in the full project proposal and it should address and document all lifecycle phases (Fig. 4.4.1). Principal investigators should describe in detail which financial means and resources will be needed during the operational phase for the data management. A dedicated person for data and also sample management in the project can be very useful. The DMP should include budgets for human resources, hardware, transport of devices such as the core scanner as well as the travel costs for the Data and Sample Management (mDIS) training course (s. Supplement S1). Within the training course, participants will develop the final Data Management Plan and the details for data acquisition.

**Phase 2: Primary Data Acquisition**

With the plan in place, the next phase is the data acquisition, which starts with the first shift on-site and continues until after the sampling party (Fig. 4.4.2). As long as the fieldwork proceeds, project scientists will collect data in a way that is commonly unique and project-specific.

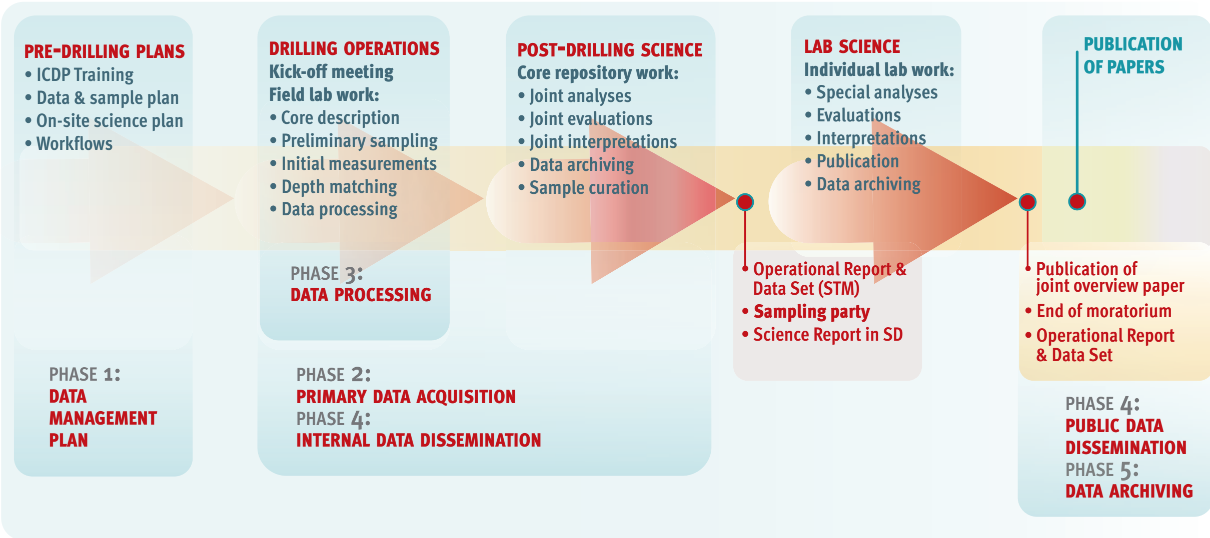


*Fig. 4.3.2: Data Management Phases during an ongoing ICDP drilling project*

The data comprises a multitude of drilling parameters as well as details on the recovered material, sampling and lithological descriptions.

Many drilling projects decide to limit the onsite workflow to capturing the technical parameters of the drilling operations and produce only essential reports, citing recovered sample material such as cores, cuttings, mud, fluids, and gases. Other drilling projects perform imaging and initial lithological descriptions onsite as additional part of the project documentation. Additional measurements for continuous petrophysical and/or geochemical properties can be included. If sampling is allowed for reasonable special cases, these samples must be tracked.

A basic architecture of a typical data acquisition and workflow model is shown in Fig. 4.4.3. If data acquisition such as core logging, scanning and description is not possible in the field, it can be carried out simultaneously or subsequently under more reliable conditions in the laboratory or core repository.

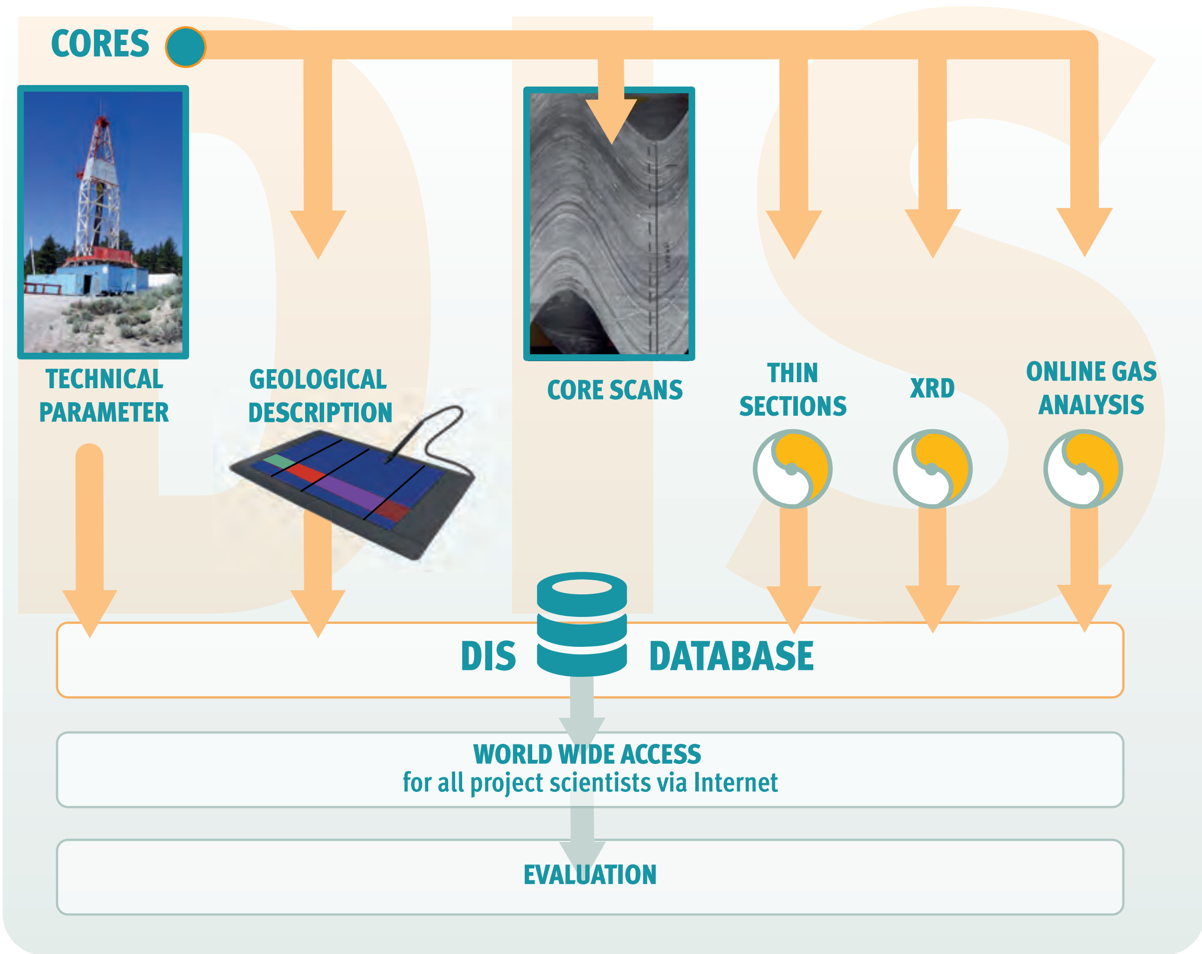


*Fig. 4.3.3: Workflow example for the data management of the Long Valley project in ICDP*

Consequently, the expedition is divided into two phases: drilling operations and laboratory work. This often takes place with a significant lag time due to the transfer of all the sample material from the remote sites to the target lab.

Data acquired during the laboratory work is also part of the Operational Data Set. All data gathered in the field and the laboratory will be stored in the mobile Drilling Information System (mDIS), which is established on a local server on-site, nearby the drilling operations or in field laboratories. In case of a stable internet access, the mDIS server can also be set up as a remote server, e.g., run by ICDP and the data is then accessible remotely via a web browser by authorized project members, who are not on-site and can use it for remote cross-checking and quality control (QC) purposes. Regularly, staff uploads the field data to the ICDP project web site where it is accessible to all science team members (e.g., http://cosc.icdp-online.org/).

**Phase 3: Data Processing**
Data acquisition is directly followed or accompanied by the data processing phase (see Chapter 4.6). Processing may include depth matching of measured core depth with the depth gathered from geophysical logging or by creating composite logs from a number of neighbouring drill holes. That processed data is the foundation of all subsequent scientific work and, thus, needs to be finalized before the sampling party.

**Phase 4: Data Dissemination**
For Data Dissemination, ICDP creates a web site for each ICDP project after the first approved workshop proposal at: www.icdp-online.org/projects/.
Generally, a project figure, abstract and

logo make up the cover page, while topics such as News, Scientists, Press & Media, Publications, Workshops, etc. are updated as required on the project page. With the project developing and according to actual project activities, the project web site grows; messages of the day, a photo gallery and internal data are added. When the project is ongoing, it usually receives more attention from the public. Accordingly, the project will also be featured as a Highlight on the ICDP web site as well as on the ICDP social media accounts Facebook, LinkedIn, and twitter.

To enhance outreach, project PIs can also maintain own websites and/or use their preferred choice of modern social media. The ICDP website creates an abundance of links to the project-specific contents of these external media.

New scientific data is usually confidential. Therefore, ICDP puts such data sets under secure access for registered science team members only. This protected area serves as a knowledge transfer platform within the science team and is very useful to include science team members that are not onsite and for selecting samples. If the internet connection onsite is stable or if the mDIS is hosted on a central server, it is also possible to directly grant access to the mDIS for different user groups.

After the moratorium period the Operational Data Set is published together with the Operational Report as supplement to the Science Report. PIs are encouraged to publish these reports in the Scientific Drilling Journal (see Chapter 2 and the guidelines on report writing in Supplement X), where DOIs are assigned. Afterwards, modifications on the data set are usually not possible anymore as it is the common foundation for all scientific work to follow.

**Phase 5: Archiving**

Data archiving is an important part of the lifecycle because it ensures that no data will be lost and available after the project ends. All raw and processed data should be stored in an archive for secure long-term preservation. At the end of a successful data management lifecycle the scientific output, e.g., publications, will stimulate discussions and ideally cumulate in further projects.

**Data/Sample Training Course (mDIS)**

Within the training course the data and sample management cycles and the details for data acquisition, core handling procedures and on-site workflows will be discussed and developed. Furthermore, the tool for data acquisition, the mobile Drilling Information System (mDIS), will be presented and adapted for the specific requirements of the project. At the end of the course, a final version of the mDIS should be installed on the laptop that will be exclusively available for data management at the drill site/laboratory.

For all coring ICDP drilling projects this training is mandatory and its cost should be part of the budget plan. For the training, the general regulation is that the project covers the travel costs to and from Germany (including visa). ICDP covers the accommodation in Potsdam, the daily rate for meals, all training materials, and local transport. The training will last 5 days and is usually hosted by the OSG data management group at GFZ in Potsdam, Germany. The mDIS training course should take place about six months prior to drilling.

Participants should include at least one PI and a person responsible for the data and sample management in the field and in the laboratory (if applicable). In addition, 3 - 5 members from the on-site science team should participate. It is preferential if at least the data manager and one additional person have some skills in computer handling and data acquisition. It is intended that they provide guidance and education of additional staff entering data, oversee consistency and quality/security of the data acquisition and function as relay for distributing reports. Besides the training before the drilling operation, the ICDP OSG also offers support during the field operations as well as remote support after the initial set-up in the field.

*Fig. 4.3.4: The mobile Drilling Information System is platform-independent, open source and can be used on different devices due to its responsive design.*

**The mobile Drilling Information System**
The mobile Drilling Information System is a database management application developed and provided by ICDP for capturing and curating essential data on geological samples, drilling progress, and related datasets such as images or geophysical well logs. It is easily adaptable for distinct project needs and ensures that all data gathered during the project is compiled in the Operational Data Set, which is accessible for all Science Team members during the projects' operational phases and for the whole science community at latest after the moratorium period.

The mDIS will be deployed and modified during the mandatory training course with the possibility for remote follow-up training and online support during the field operation.

**The mDIS concept**
The Drilling Information System is designed to be used onsite in parallel with daily operations to perform the data acquisition alongside a defined workflow. This is helpful for avoiding the excessive creation of non-synchronized and non-authorized data files.

The mDIS structure is hierarchical and reflects the ICDP naming conventions. It starts with program as highest hierarchy level, followed by expedition, site, hole, core, section, sample, etc. levels (Fig. A, see Chapter 4.5, Sample Management for details on naming conventions).

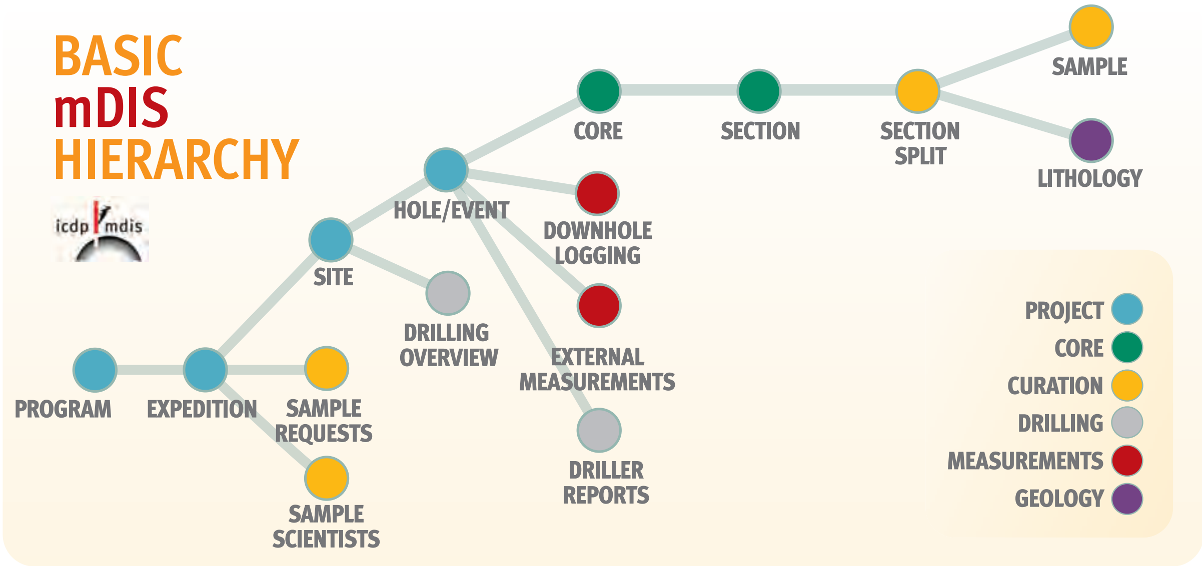


*Fig. 4.3.5: Hierarchical structure of mDIS following the overall ICDP naming conventions. Colors indicate thematic groups of data (table sets).*

Each hierarchy level is defined by a data table and an entry mask (form), which can be customized by trained users within the mDIS application for project specific needs in three steps:

- Create a table
- Create a form
- Use form to insert data

Data to be inserted includes all drilling and sample relevant information as the technical drilling parameters, core data, core scans, lithological description, photos and initial measurements (Fig. B).

Within the data-acquisition workflows, certain automated data-consistency checks and human quality controls ensure the data quality. Data integrity is enforced in terms of measurement units, date and time formats and naming conventions at the time of data capture, before it is safely stored in the relational tables of the mDIS project database. Furthermore, mDIS automatically assigns International Geo Sample Numbers (IGSN, Chapter 4.5) that can be exported and directly send to an allocation agent for registration.

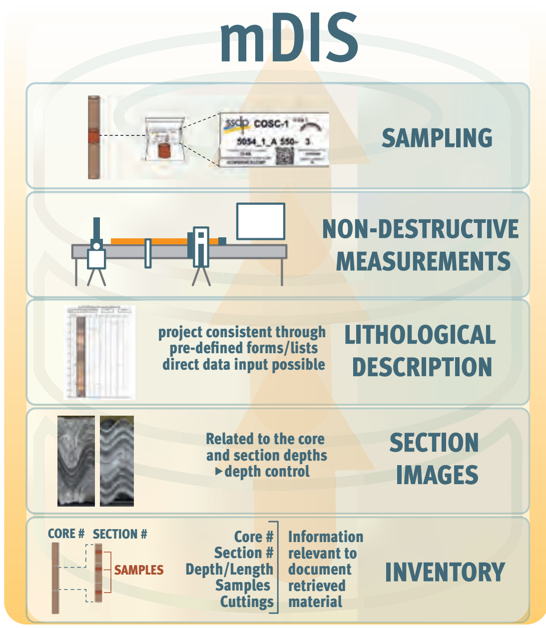


*Fig. 4.3.6: Data from various sources is stored in the mobile Drilling Information System to build a complete data set available for all Science Team members during the operational project phase.*

Once the data is stored it is possible to print labels for sections and samples including a QR code for easy access and findability. Additionally, the data can be printed in different kinds of reports and can be used as source for the Operational Report (Chapter 2, Operational Report) since the data can easily be transferred into external data-processing applications and spreadsheets.

**mDIS set up**

mDIS is platform independent, responsive and open source (Fig. 4.4.6). It is set up in a server-client environment, where a dedicated personal computer acts as mDIS server. The native mDIS runs on Linux, but it is deployed as a virtual box instance, which can be installed on Windows, Mac and Linux systems and contains the data base system and the mDIS application. As long as a device has a browser it can be used for accessing mDIS as client to view, update, edit or upload data.

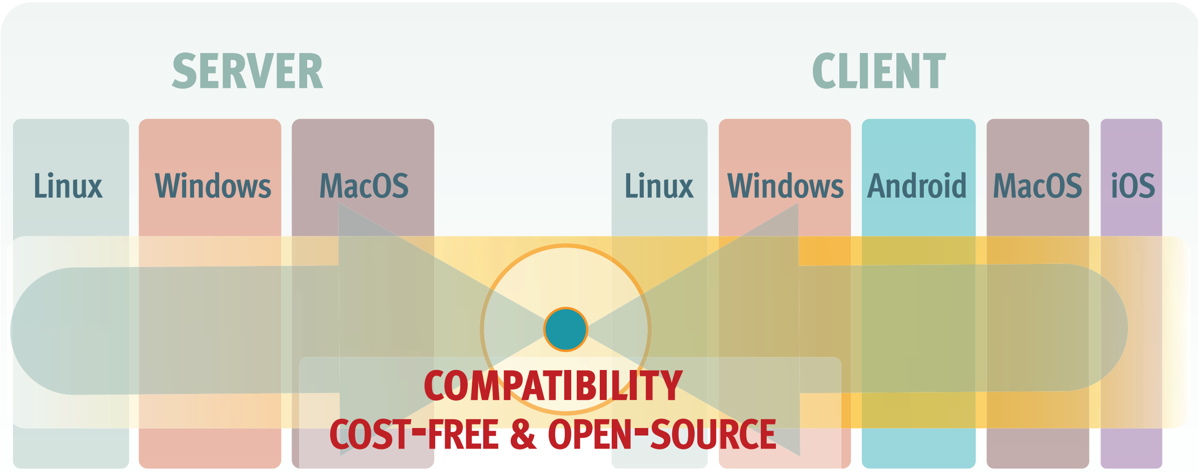


*Fig. 4.3.7: The main mDIS (server) will be installed on a virtual box, which can run on Linux, Windows and MacOS. As long as a device has a web browser it can access mDIS.*

**Field Application**

The mDIS can be used either as standalone version on a laptop, via a local network or via the internet. The standalone version is useful for data entry in remote areas without internet access, or for any small project, where all data can be inserted locally on one PC. However, if data acquisition facilities are being distributed across a larger area, such as a large field site (and separate labs), or a fleet of research vessels, it is useful to access the mDIS server via a wide area network or via the public internet. Other external devices such as core scanners or core loggers can also be included into that network. If the mDIS system at the field site can be connected to the wider internet, it is possible to upload daily updates and progress reports to the dedicated project website and/or archive servers or grant access to mDIS via a web browser for the whole Science Team. It is also useful for remotely supporting the mDIS operator and the mDIS system itself.

**Technical specifications**

Technically, mDIS is a relational database backed web application built on a LAMP stack (Linux, Apache, MariaDB, PHP). On the client side, mDIS is based on a Javascript framework (VueJS) that, in conjunction with the Yii PHP framework, allows for reactive two-way data binding. mDIS can be deployed in desktop environments and on servers. On mobile devices, mDIS can run as a Progressive Web App (PWA), which works almost like a native app. mDIS has REST application programming interfaces (APIs) for third-party application developers and external data providers. These APIs can be used for importing data from legacy DIS installations and other data sources such as text files and collections of core imagery.

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# Sample Management and Distribution

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Science is characterized by the acquisition of high-quality data, its interpretation in context with existing knowledge, and its publication. In the majority of cases, the quality – and quantity – of these data depend on sample quality, identification and storage. In the context of an ICDP project, sample management is a long-term task that starts with a management plan as part of the project proposal and extends throughout the expedition, project duration and beyond.

Holistic sample management plans (SMP) contribute significantly to the success of the project and allow the best possible use of the samples and consequently the data obtained. Therefore, sample management and data management as described in the previous chapter deserve a high level of attention from the project leaders and the entire science team. Both, sample and data management plan (DMP) and the SMP, are dynamic documents adapted throughout the proposal, planning, project and post-drilling phase. This chapter summarizes the key components of a successful sample management plan for an ICDP drilling project over the entire lifecycle. The application of these key components allows the FAIR principle (Findability, Accessibility, Interoperability, and Reuse) to be satisfied, which is in line with ICDP´s sample and data management policy. For a best practice example of the on-site core handling the reader is referred to Chapter 4.5.

**Sample Management Plan**

Starting with the full proposal, principal investigators should include the financial means and technical/scientific personnel needed for the implementation of the SSs SMP.

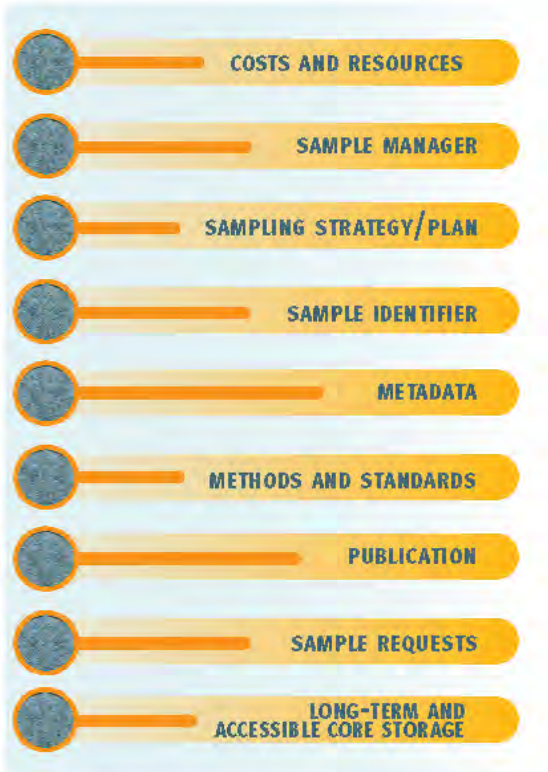


*Fig. 4.4.1: Sample Management Plan elements*

This includes costs related to sampling (e.g., instrumentation and consumables), shipping, long-term storage in an appropriate core repository and costs for a sampling party at the end of the drilling and lab science phase. The budget should also cover travel costs related to the obligatory training course on data and sample management offered by OSG (Data and Sample

Management training course, see Chapter 4.4). Regarding the personnel resources, the PIs should consider appointing an exclusive sample manager (or sample & data manager), who is responsible for the implementation of and adjustments to the SMP and oversees the preparation for the field work, the sampling workflow, sample curation, day-to-day business at the site, during the sampling party and beyond.

An excellent example highlighting the importance of well-designed core handling and sampling curation for scientific projects is the NASA curation plan for extraterrestrial samples as provided by Allen Carlton et al. 2013 (Curating NASA´s Extraterrestrial Samples, EOS 94 (29) doi:10.1002.2013eo290001)

- 'Through nearly a half century of work on analyzing and curating samples from places beyond Earth, a few key messages stand out.
- First and foremost, the main point of any sample return mission is laboratory analysis. Everything must be designed, built, and operated to get the highest-quality samples to the best laboratories.
- Further, curation starts with mission design. Samples will never be any cleaner than the tools and containers used to collect, transport, and store them. Scientists and engineers must be prepared in case missions do not go according to plan. Really bad things can, and do, happen to missions and to samples. Careful planning and dedicated people can sometimes save the day, recover the samples, and preserve the science of the mission. Every sample set is unique. Laboratories and operations must respond to the diversity and special requirements of the samples.
- Finally, curation means that those involved are in it for the long haul. Samples collected decades ago are yielding new discoveries that alter scientific understanding of planets, moons, and solar system history. These discoveries will inspire new generations of scientists and research questions and will drive future exploration by robots and humans. Curation is—and will remain—the critical interface between collecting samples and the research that leads to understanding other worlds.'

Personnel resources and costs will be associated with this post. The SMP may also consider other staff responsibilities with respect to core sampling and data entry (the Science Team). Early on, the PIs, the sample manager and experienced technical personnel need to develop a sampling strategy to facilitate the organizational operation and provide all resources needed for sampling to ensure high quality samples and allow for the largest scientific output possible. The strategy should consider which steps and samples need to be taken at the site. The sample quality is often higher and logistics easier if sampling takes place once the cores were transferred to an appropriate laboratory or core repository.

The projects main scientific objectives determine the sampling strategy; the logistics of sampling and the sampling plan depend on availabilities, lead times and environmental conditions and are therefore subject to change. The finalization of the sampling plan and the core handling are topics of the training course on data and sample management that the OSG provides for each approved ICDP project (see Chapter 4.3). Chapter 4.5, and particularly Figures 4.5.10 and 4.5.11 provide sampling plans.
To allow for the best and most effective handling and utilization of the core material, the core needs to be persistently and distinctively marked and curated together

with the appropriate metadata. This standardized and unique sample identification and metadata collection is indispensable for a successful drilling project. It is also a prerequisite according to the FAIR principle (see Fig. 4.4.3).

The IGSN (International Global Sample Number) is a global persistent identifier for all kinds of samples with any IGSN number being unique and registered by the IGSN e.V. in cooperation with allocating agents, one of them being the GFZ in Potsdam, Germany. An IGSN is automatically assigned to any hole, core, section, sample, and should also be assigned to mud, cutting, gas or other material extracted from the drill holes and entered in the obligatory mDIS database (see Chapter 4.3). This applies to any on-site sample as well as samples taken in the core repositories during the sampling party or any other time. When forwarded to the registration office, the metadata will be registered with the IGSN. This makes the sample and metadata 'findable' and 'interoperable' (Fig. 4.4.2) for the science community and others. Usage of IGSNs combined with the long-term storage of the samples in a publicly accessible core repository are essential parts of the FAIR principle applied in ICDP projects.

The data, associated metadata of all sample material taken as well as standards and methods used for core or sample measurements are made available to the science team – and later on the public – as part of the project's Operational Data Set and Operational Report (see Chapters 2 and 4.3 and Supplements for Guidelines).

Since part of the IGSNs used by ICDP is a random number, human readable combined IDs will be assigned to cores, sections, and samples for quick and easy identification. The combined IDs used by ICDP are comparable to e.g., the naming conventions of IODP.

*Tab. 4.5.1: Conceptual schemes and terms of ICDP, IODP, and the German data center PANGAEA*

| ICDP / IODP | PANGAEA |
|---|---|
| Program | |
| Expedition | Project /Campaign |
| Site | Site |
| Hole | Event |

One or more Holes/Events can take place at a site, such as 'Drilling a Hole'. In both, ICDP and IODP models, the terms are arranged in a relational hierarchy:

- Expedition is the operational phase of a scientific drilling project, which has a number assigned to it (e.g., COSC-1: 5054 (Fig. 4.5.XX)
- One or more Sites (ICDP: Number) can be visited during an Expedition
- One or more Holes (ICDP: Letter) can be drilled on each of the Sites

*Table 4.5.2: Conceptual schemes and terms of IODP, ICDP, and CSD Facility in Minneapolis*

| | Expedition | Site | Hole |
|---|---|---|---|
| **IODP** | 372 | U1519 | A |
| **ICDP** | 5054 | 1 | A |
| **LacCore** | GLAD5-BOS04 | 1 | A |

Since naming conventions in different core repositories can be quite different, the mDIS allows listing a second unconstrained/free-formatted naming scheme as long as it is used consistently throughout a single expedition or project.


*Fig. 4.4.2: Sample label with ICDP sample ID (middle), IGSN number, and IGSN QR code (lower)*

To be able to keep track of all samples and to append them to the database, there is a central rule: 'No sampling without sample requests'. In order to achieve this, it is recommended to repeatedly publish 'Calls for Sample Requests' starting early on in the project, even before the start of planned drilling operations. The majority of samples will be taken during the sampling party that preferably takes place soon after the cores have been transferred to the core repositories, whereas on-site sampling should be restricted to unavoidable, immediate sampling based on the SMP.

Reasons for repeated 'Calls for Sample requests' include:

- To review the individual sample requests in consideration of the project objectives
- To detect sections that would be over-sampled or are not requested sufficiently
- To review and adjust the general sampling strategy
- To improve the on-site and laboratory sampling procedure

Logistically, an early first 'Call for Sample Requests' is especially important for samples that are requested to be taken on-site simultaneously with the drilling operations. At this point, the sample manager can validate whether or not this is inevitable and how to best integrate the sampling into the on-site workflow. During the drilling and after the collection of the Operational Data Set, additional 'Calls for Sample Requests' allow for a refinement of the sample distribution. This could also minimize the number of additional sample requests during the sampling party, and thus, make sampling more efficient.

The project's Operational Data Set is the collection of information, which the sampling strategies of the science team members is based upon. It will be made accessible for science team members only during the moratorium period on the ICDP projects website and maintained by the OSG. The PIs assemble the science team. Amongst others, the data set includes: uploaded images, scans, lithological descriptions, core logs, well logs and corrected sample depths. The data provide basic information about the quality of recovery and geo-properties that can support the selection of appropriate sampling spots. The Operational Data Set will be published online after the moratorium. See Chapter 4.4 for details on data management.

*Table 4.5.3: Selection of some of the core repositories curating ICDP samples*

| Repository Name | Funding Program | Host Country | Condition |
|---|---|---|---|
| **Bremen Core Repository (BCR)** | IODP | Germany | cooled |
| **Gulf Coast Repository (GCR)** | IODP | U.S.A. | cooled |
| **Kochi Core Center (KCC)** | IODP | Japan | cooled |
| **CSD Facility (formerly LacCore and CSDCO)** | NSF, CSD | U.S.A. | cooled |
| **Rutgers Core Repository** | IODP, NJGWS | U.S.A. | cooled |
| **National Core Repository** | BGR, GESEP | Germany | not cooled |

The early planning of the long-term core and sample preservation and storage is crucial to guarantee the long-lasting success of a project. Unlike IODP, ICDP does not maintain its own storage sites (repositories) for sample material. Accordingly, each project has to take care of appropriate facilities and accessibility for a long-term period after the end of the project (10 years minimum). However, ICDP samples can be stored in trusted facilities of IODP, LacCore and others that operate according to scientific best practice and warrant long-term access.

A list of major core repositories already storing ICDP cores is provided in Table 4.5.3. For a more comprehensive collection of suitable repositories, the PIs are referred to the ICDP repository website and the OSG team as needed. The listed repositories host and preserve sample material, conduct professional sample curation and are accessible for any scientist.

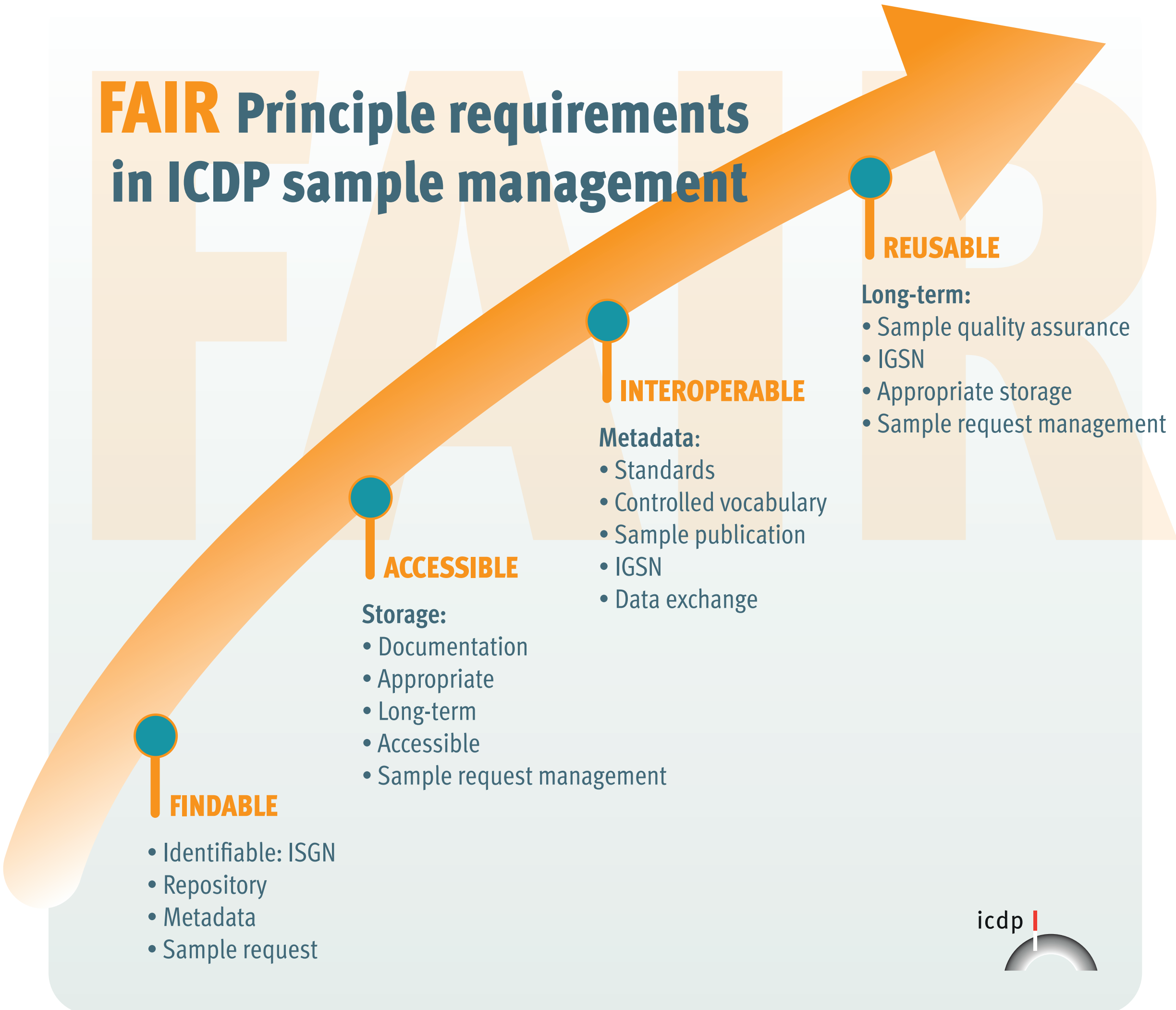


*Fig. 4.4.3: How key components contribute to the FAIR principle in ICDP sample management*

**Depth Scales and Measurements**

Depth matching is an important issue of wellbore data consistency and described in detail for IODP drilling. Typically, core and sample depths can be based on a number of different approaches including:

1. the cumulative length of the drill pipe (Drillers Depth below rig floor, DRF)
2. the depths below surface/lake floor based upon the drill pipe length minus distance from rig floor/drillers reference point to the surface (minus water depth given lake drilling) (Drilling depth below surface, DSF)
3. Core recovery might be >100% compared to the advances given by the drillers if the curated length is greater than drilled length (Core depth below seafloor/surface- A, CSF-A). The depth is given as the top depth of each core (DSF) plus the curated section length (+ sample/data offset). If the core recovery is greater than advancement, cores can overlap (correction method:

overlap). Units used are either m CSF-A or mbsf/mbs.

4. Core recovery is not allowed to be greater than drilling advancement. Instead of an overlap, a compression algorithm is applied such that core recovery equals 100%. Core depth below seafloor/surface-B, CSF-B) or (correction method: no overlap). Units used are either m CSF-B or mbsf/mbs.
5. If there is no drill core, lag depth applies, e.g., for cuttings or fluids. The lag depth is a calculated depth derived from the drill mud circulation.
6. True Vertical Depth (TVD) can be calculated if the trajectory of the hole is known.
7. Subsequent wireline logging can be used for depth corrections by referring the length of wireline used during logging equivalent to the DRF and DSF (Wireline log depth below rig floor, WRF; Wireline log depth below surface/lake floor, WSF, also called Log Depth). Wireline log depths are usually continuous and most accurate. If log depths are available, it is recommended to correlate or match all other depth systems to log depth. The corrected depth is in meters corrected depth (mcd) or in mbs, mbsf or mblf.
8. If there is more than one borehole, depth correlation of data from logging or physical property measurements can be used to calculate the Composite Depth that splices selected sections retrieved from multiple holes. Units are either core composite depth below seafloor/surface, (CCSF) or meters composite depth (MCPD). For details on the splicing method see Chapter 4.5.4.

**Workflow for depth corrections**

1. Transfer any depth measures in meter units
2. Calculate DSF and CSF depth scales
3. Define reference level for all holes of a site
4. Build composite or spliced profiles in case of multiple, partly overlapping holes on a site.

Simple depth calculations are supported by the mDIS. In cases 3 and 4 software tools such as WellCAD (RockWare) and/or CORRELATOR and CORELYZER (open source from CSD Facilities) assist the depths calculations. Both software programs allow for the correlation of all types of depths. Using a selected master downhole log can provide the true vertical depth.

Spliced data profiles (including line scan images) can be generated by using, e.g., CORRELATOR and CORELYZER to produce a composite site image overlaid by the various data sets. This also extends into the task of 'Depth -&- Data Matching', which is a mandatory prerequisite for the overall quality of the data set(s) obtained in the field and laboratories after the field operation has been concluded. For detailed information on depth calculations and spliced data profiles see Chapter 4.6.4.

***Field Report: How to make the most of your core material***

*When beginning to plan a drill project some aspects are prone to falling into oblivion: the data and sample management and the practical work involved from predrilling until the scientists can actually work on samples.*

*On the drill site, PIs, Co-PIs or other scientists will want to prioritize tasks such as – deciding where to drill, how far to drill or initial logging. It is equally important and almost as time consuming to take care of the initial core inventory, measuring, counting and packing core sections, entering box numbers, slot numbers,*

*box positions, depths, times, drilling parameters, etc. into the database, communication with the OSG, taking contamination samples, labelling boxes, stacking and preparing core boxes for shipping and so forth.*
*This work continues in the core repository collecting the basic data; labelling, scanning and logging 1000s of meters of whole and split sections, entering data, uploading files, handling and documenting sample requests. Samples need to be entered, cut, labelled, placed in sample bags and packed for shipping. The obligation to store and make the cores accessible for the public remains for at least 10 years. If the project has chosen to use a core repository, the hours needed for data and sample management will be considerably less once the moratorium has passed. Nevertheless, sample requests and follow-up are still tasks that need to be handled.*

*Without the use of a core repository, sampling parties and sample requests need to be organized once or twice a year. Realizing sample requests, entering new data into the database, cutting, labelling and bagging samples, preparing customs documents and shipping are the tasks that will arise again. Regular database backups, new data entries, handing out overview lists and answering questions about samples received are regular exercises throughout the year.*

*In the FarDeep project, the idea emerged to ask scientists to send back unused or leftover materials. Since all projects run the risk of handing out samples that are never processed, it seemed important not to waste these precious materials. This system of sample recycling does mean scientists using samples need to be contacted regularly, asked for return of unused material, incoming samples need to be weighed, screened, labelled and re-entered into the database as existing samples. Between 2014 and 2019 an average of 600 of these returned samples have been handed out each year in addition to new samples that were taken. Many researchers are happy to subsample existing sample sets, especially when they are already crushed or powdered for analysis. This might not sound a lot, but after all - drilling was completed in 2007 and the interest still persists as recent (2020) publications show.*

*In conclusion, it can be said that the curation of data and samples is demanding, but a project is worth nothing without it. An experienced data and sample manager can help to plan the practical aspects of sampling strategies for the project from the time the drilling starts until far beyond the active phase of the project, allowing scientists to concentrate on drilling and science and at the same time make the most of the treasured core material. This person should stay with the project for the entire time it is still running. Continuity will save time, resources and will help not to lose valuable information along the way. Initially, 500-700h a year should suffice to carry out these tasks and can probably be reduced over the years. While a background in geoscience might be helpful, being involved in the science of the project might not. At times, conflicts of interest can arise and a technician could feel more objective or approachable. Since that person will be the contact person for sample requests, data and sampling routines, this can be an advantage.*

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CHAPTER 4.5

# Handling of cores and cuttings, and core correlation

**Katja Heeschen*, Alexander Francke+, Henning Lorenz#, Simona Pierdominici*, Anja Schleicher§, Cindy Kunkel*, and Ronald Conze***

This chapter provides two examples of workflows on core handling, one on hard rock (COSC, Sweden) and the other on soft sediment core material (SCOPSCO, Lake Ohrid, Macedonia). In addition, examples on handling cuttings from three different drilling projects (SAFOD, San Andreas Fault, USA; DFDP, New Zealand; NanTroSEIZE, Japan) described below may serve as a guideline for similar drilling projects during their planning phases (Zoback et al. 2011; Townend et al., 2009; Tobin & Kinoshita, 2006). Illustrated instructions (core marking, naming convention, packing of core boxes, etc.) are provided in Supplements S2 to S7.

### 4.5.1 Core handling in crystalline rocks

The Collisional Orogeny in the Scandinavian Caledonides (COSC) scientific drilling project drilled its first drill hole, COSC-1 (ICDP 5054-1-A) in 2014 (Lorenz et al., 2015a), in the vicinity of the abandoned Fröå mine, close to the town of Åre in Jämtland, Sweden. The drilling project is a typically slim hole hard rock coring project using a wireline exploration triple-tube diamond coring system. During the drilling operations an elaborated core handling workflow was applied. The following chapter is an excerpt from the COSC-1 Operational Report (Lorenz et al., 2015b).

#### COSC on site science team

The scientific operations were coordinated by Uppsala University, Sweden. The on-site scientific work was performed in two 12 h shifts per day. Normally, three scientists were on-site at any time during the operational phase. Two groups were rotating on a 10-day schedule, partly with changing personnel. The first group began its work two days before planned spud in. The complete on-site scientific work from mobilization to demobilization is estimated to about 4.75 man-years (see COSC-1 Operational report for details; Lorenz et al., 2015b).

*Fig. 4.5.1: First COSC drill core (gneiss below cement) in opened inner tube of a triple tube core barrel assembly. Clearly visible is the split aluminium liner protecting core from external forces, the second tube, and the drill string tube, hence 'triple tube'.*

#### COSC workflow drill core handling

The on-site science team received the drill core from the drilling team at the drill rig, noting top and bottom depths and possible comments on the core run protocol. For cores drilled with 3 m triple tube core assemblies, this was done on the pipe handling rack, where the drill core in its aluminium split-liner was hydraulically extracted from the inner tube (Fig. 4.5.1).

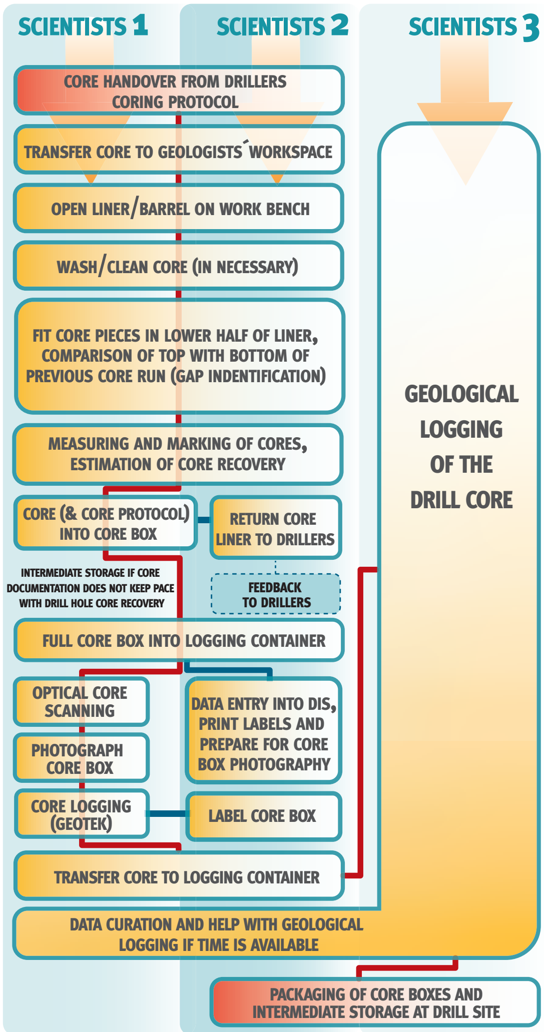


*Fig. 4.5.2: Workflow for the COSC-1 drill core handling procedure*

The closed liner was then transferred to the geologist's core handling table for further processing (Fig. 4.5.2). The 6 m core barrel assembly had to be split in two halves. To guarantee that core extraction without an inner liner was done in the most careful way, the drilling team removed the core from each half of the inner tube piece by piece, handing them immediately over to the science team who placed them in empty core liners (from the triple tube system), always under rigorous control of top and bottom. In this way, the drill cores from the double and triple tube systems could be processed in the same way.

At the geologist's working table, the core pieces were restored to their original position (with few exceptions where this was not possible) and marked with two coloured lines for orientation (red line on the right when looking upwards, and blue, Fig. 4.5.3). Not until this was finished were the other tasks performed. These were (1) measuring the total length of the drill core along the red line, (2) washing with a sponge and clear water and subsequent drying with a paper towel (usually enough since the only additive in the drilling fluid were biodegradable polymers) and (3) placing the drill core into core boxes including the labels (on foam blocks; Figs. 4.5.4 & 4.5.5).

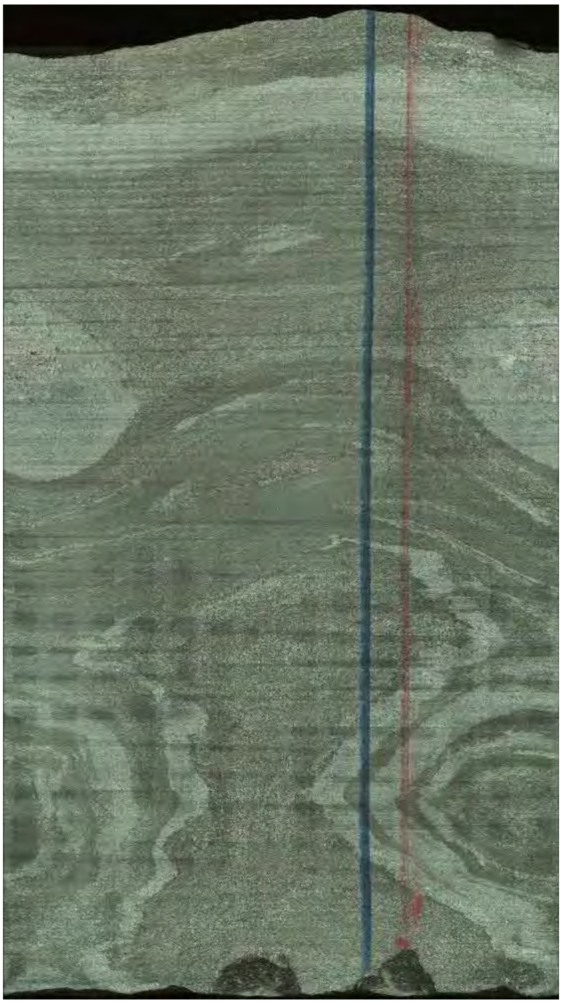

*Fig. 4.5.3: Whole round optical core scan of gneiss core section showing double reference line in upright position with red line on the right*

From the geologist's working table, full core boxes were transferred to the first science container. Here, the core run protocol was scanned and archived, and its data together with information about the core's position in the respective core boxes was registered in the Drilling Information System (DIS).


*Fig. 4.5.4: Core boxes 648 and 649 from COSC-1. The core boxes are used in portrait format (=upper left corner = Top, lower right corner = Bottom. Top and bottom of core runs are marked with labelled foam blocks. Each box was photographed with the cm/ft ruler and a standard colour chart.*


Fig. 4.5.5: *Sample location filled with a labelled foam block showing the sample number and IGSN (lower left: ICDP5045EX2W501)*

Unrolled core scans were acquired for each section (Fig. 4.5.3) after drying with a hair dryer and the images were added to the DIS. Afterwards, each core box was photographed on a repro-stand and the photos added to the DIS (Fig. 4.5.4). Colour profiles were calculated along each core section with the help of a GNU Octave script. Subsequently, geophysical parameters of the core sections were logged on a Geotek MSCL-S core logger (provided by ICDP).

For the core documentation, the core boxes were transferred to the working place for geological drill core logging. The geologists entered this description directly into the DIS. Finally, the core boxes were packed for transport and temporarily stored at the drill site.

**COSC sampling**

All samples in the COSC scientific drilling project are marked with an International Geo Sample Number (IGSN), a hierarchical unique identifier (Combined-ID) (Fig. 4.5.5) that is used to track samples and relationships between samples (see also: Chapter 4.5).

On-site sampling of the drill core was very restricted and only permitted for the following purposes: study of changes in thermal conductivity in relation to time after drilling (sample to be returned), matrix gas extraction and analysis (samples have been returned), microbiology (destructive). In addition, the on-site science team took DNA and ATP swab-samples on fracture surfaces. The tracer used for microbiology was fluorescein dye. More advanced setups to employ tracers together with NQ triple tube drilling were ready for employment, but not used due to the strategic decisions to only use the faster double tube drilling in the lower part of the drill hole.

### 4.5.2 Core handling for lake sediments

The ICDP project 'Scientific Collaboration on Past Speciation Conditions in Lake Ohrid' (SCOPSCO) recovered more than 2100 m of sediments from five different drill sites between 2011 and 2013 (Fig. 4.5.6) (Wagner et al., 2014). During the first drilling campaign in summer 2011, short sediment successions <10 m were recovered using an UWITEC piston corer. This drilling technique uses a re-entry cone on the sediment floor to recover a continuous sediment record and is suitable for soft sediments down to about 20-25 m below lake floor (blf).

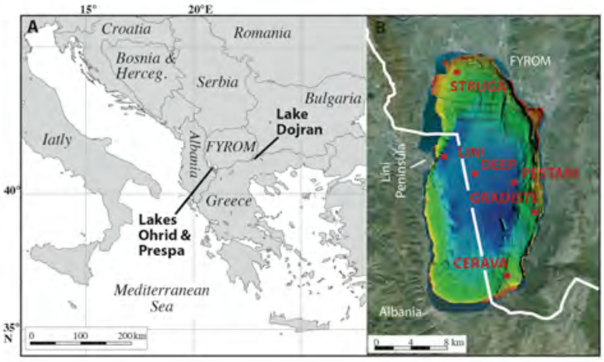


*Fig. 4.5.6: Location (left) and map of Lake Ohrid (right) with color-coded depth and drill sites, modified after Wagner et al., 2014.*

Between April and May 2013, a deep drilling campaign was carried out using ICDP's Deep Lake Drilling System (DLDS) operated by DOSECC (Drilling, Observation and Sampling of the Earth's Continental Crust's) consortium. At the drill sites DEEP, CERAVA, and GRADISTE boreholes were cored at water depths of 243 m, 119/131 m, and 131 m down to 569 m blf, 90 m blf, and 123 m blf, respectively (Wagner et al. 2014). In order to obtain a maximum composite profile recovery, multiple boreholes were cored at each drill site. At the PESTANI site, the maximum penetration depth was ~194 m blf. The composite field depth recovery adds up to more than 90 % at each individual drill site (see Chapter 12 for depth correction methods).

### Ohrid on-site science team

The on-site scientific operations were coordinated and conducted by the Universities of Cologne and Kiel (Germany), the Faculty of Natural Sciences of Skopje (Macedonia), and the Hydrobiological Institute Ohrid (Macedonia). Scientific work on the drill barge was performed in two 12-hour shifts. The platform team consisted of three scientists led by Post-Doctoral researchers and experienced PhD students. This group was responsible for the on-site documentation, core handling, and initial sampling. Additionally, the scientific shift leader was also responsible for making decisions in close collaboration with the driller team on type and progress of daily coring activities and depth calculations. General decisions about the drilling strategy and the selection of the subsequent drill holes and sites required consultations between the Principal Investigators (PIs), on-site scientific shift leader, and driller team. The shore-based PI was, in particular, responsible for the overall organization of the field campaign, including, e.g., financial and political issues and the timely fuel and drill mud supply to the drill barge.

*Fig. 4.5.7: Drill core handling on the barge. Small holes were drilled into plastic liners to prevent excessive core expansion from high gas pressure in the liner (Photo: N. Leicher).*

### Workflow for core handling on the barge

After each core run, when the drill tool was successfully pulled back to the platform and disassembled by the driller's crew, the 3m long PVC liner containing the recovered sediment core was transferred to the platform science team. Immediately, small holes were drilled into the plastic liner with a cordless screwdriver whenever gaps in the sediment structure indicated a high gas pressure in the PVC liner. Although drilling these small holes might have caused specimen contamination with oxygen, it prevented core material pushed out at top and bottom of the PVC liner (Fig. 4.5.7).

Simultaneously, caps were attached to the bottom and top of the PCV liner. The 3m long PVC liner was then split into 1m long core sections. Gaps in the sediment succession, which unambiguously occurred due to the gas pressure in the PVC liner, were closed by gently pushing the sediment back in position with a sediment pusher. Finally, caps were taped tightly on top and bottom of each core section, and then cores were labelled following ICDP standards (Fig. 4.5.8).

Oriented samples were taken directly on the platform from the core catcher (CC) by pushing small cubic plastic vials into the sediment. Subsequently, the remaining sediment material from the core catcher was placed into a plastic bag. The cubic plastic vials were shipped to the GFZ in Potsdam, Germany, for initial paleomagnetic analyses, and small aliquots were used for total inorganic carbon and total organic analyses at the University of Cologne. A first description of the recovered sediments from the core catcher provided first insights into the lithology, which is a prerequisite for decisions about succeeding drill progress and drill strategies. This brief material description was also used to provide a first overview on the recovered sediments down to the base of each hole (see for example Wagner et al., 2014).

In addition to information on the lithology, on-site documentation of the recovered core sections highlighted problems that occurred during the drilling activities or calculated drill depths. Depth calculations were crosschecked between the science and driller team before each core run.

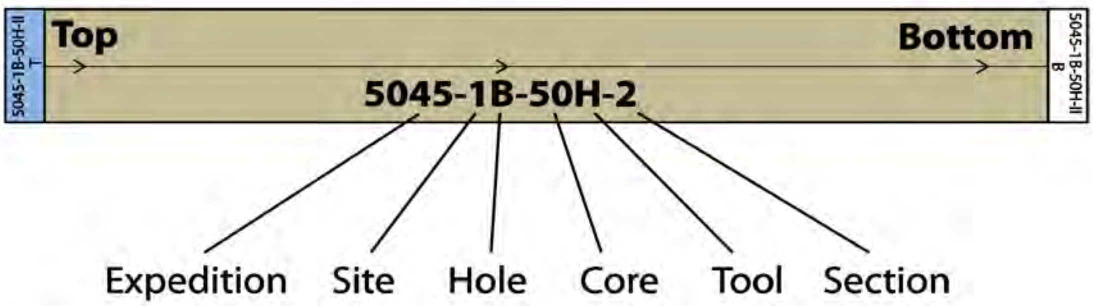


*Fig. 4.5.8: ICDP standard core labelling routine. Arrows point to the bottom of the core, blue caps are attached to the top, white caps to the bottom of each core section.*

The basis of the depth calculations is the length of the drill pipe ($P_{lenght}$) and of the Bottom Hole Assembly ($BHA_{length}$), i.e., the lowermost drill pipe to which the drill tool is connected during the drilling activities (Fig. 4.5.9). Corresponding calculations always refer to the driller's mark on the barge, which must be noted in the drill table in order to keep track of the driller's depth. The 'stick down" and 'stick up" refer to the distance between the drillers mark and the lowermost and uppermost end of the last drill pipe of the entire drill string, respectively. The air gap is measured routinely during the drilling operations and corresponds to the distance between the water surface and the drillers mark (Fig. 4.5.9).

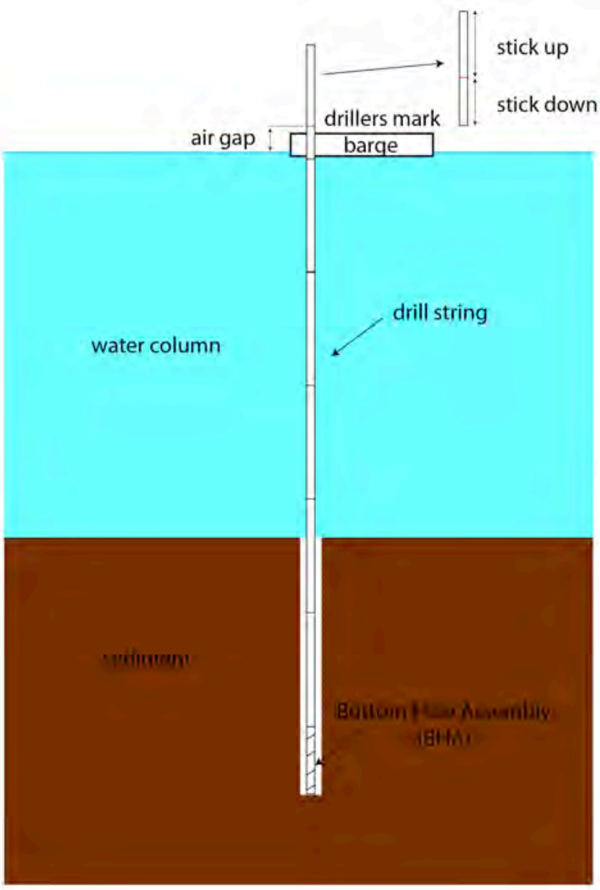


*Fig. 4.5.9: Simplified scheme for the illustration of the drill depth calculations*

In the first step, the water depth ($w_{depth}$) at the coring location is determined by using the equation (1):

$$w_{depth} = (P_{length} * P_{amount}) + BHA_{length} + \text{stick down} + HPC_{max\ length} - \text{air gab} - \text{recovery}_{1st\ HPC\ run} \quad (1)$$

Subsequently, the drillers constant $d_c$ can be calculated:

$$d_c = w_{depth} + \text{air gap} \quad (2)$$

The drillers constant $d_c$ is the basis for the calculation of the sediment depth ($s_{depth}$):

$$s_{depth} = d_{depth} - d_c \quad (3)$$

whereby the drillers reference depth ($d_{depth}$) equals to the total length of the drill string:

$$d_{depth} = (P_{length} * P_{amount}) + BHA_{length} + \text{stick down} + b_{correction} \quad (4)$$

The bit correction ($b_{correction}$) depends on the selected coring device and refers to the distance the coring device protrudes over the BHA.

### Drilling strategy

Decisions about the onsite drilling strategy encompass the selection of the coring devise, the sediment depth to be cored, and the maximum penetration depth with respect of the individual scientific targets of the drill site. Stratigraphic information obtained from hydro-acoustic pre-site surveys are rather imprecise, and more profound decisions about the selection of the coring devices can be made based on lithological information from the core catcher material of previous boreholes. Thus, higher sediment recovery percentages are often gained in boreholes, which were drilled later during an on-going drilling campaign. If multiple boreholes can be drilled at on drill site, spot coring for gaps in the sediment sequences of the neighbouring boreholes can be conducted. In order to save time during the drilling activity, the non-coring assembly can be used between the target depths.

Onsite drilling strategy should also carefully balance the risks during the drilling and the scientific gain to be expected in order to prevent the loss of coring devices. For example, at the DEEP site in the central part of Lake Ohrid, the hydro-acoustic data imply an overall sediment infill of more than 680 m (Wagner et al., 2014). However, very coarse, unconsolidated material with gravel and pebble could have destabilized the borehole and thus, coring was stopped at 569 m sediment depth (Wagner et al., 2014).

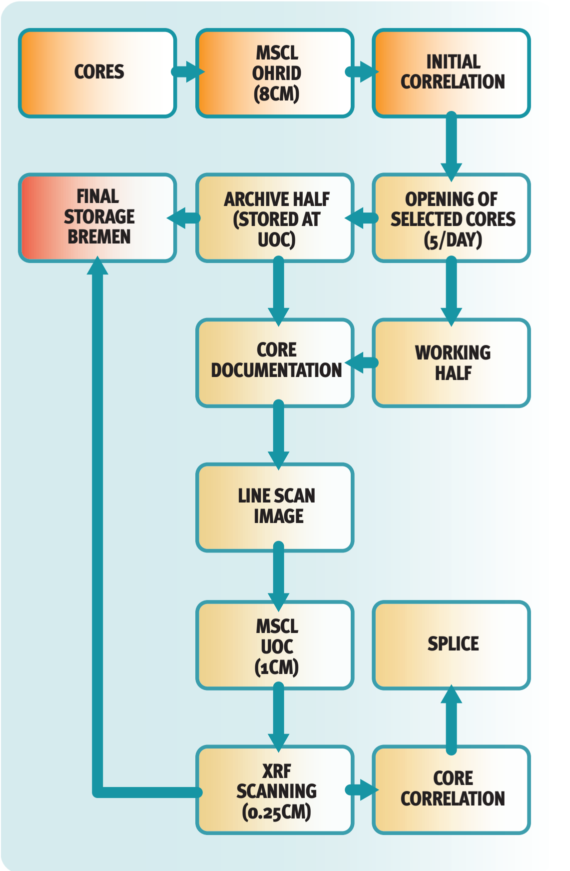


*Fig. 4.5.10: Core handling workflow during the Lake Ohrid drilling expedition.*

**Ohrid core handling at shore base**
At the shore base, geophysical parameters of the core sections were measured with a Geotek MSCL-S core logger. The volume-specific magnetic susceptibility (MS) was detected over an integral of 8 cm in 2 cm resolution steps on the whole (round) core using a Bartingon loop sensor. Smear slide samples from core catcher material were prepared for preliminary diatom analyses. The slides were directly analysed at the shore base using an incident light microscope. During the deep drilling in 2013, the sediment cores were stored in the dark at 4°C in a 20 feet overseas cooling container. At the end of the drilling activities, the cooling container was directly shipped to the University of Cologne.

**Ohrid core handling in the laboratory**
The sediment cores recovered during the SCOPSCO 2013 field campaign at Lake Ohrid are stored under temperature-controlled conditions (4°C) at the University of Cologne, Germany. The archive halves are permanently stored in the Bremen Core Repository (BCR). Core splitting, description, documentation and measurements such as MSCL and X-ray fluorescence (XRF) scanning were performed at the University of Cologne. For the XRF scanning, the resolution was set to 2.5 mm, which accounts for the homogenous structure of the sediment and is likely high enough to decipher decadal sediment property variations. Visual inspection, MS and XRF scanning data combined were used to identify horizons with tephras or cryptotephras. Corresponding results were tied into paleomagnetic measurements and chronostratigraphic tuning methods to establish an age-depth model.

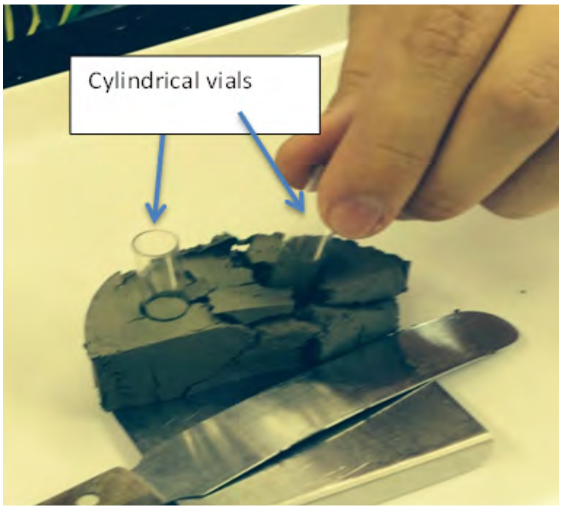


*Fig. 4.5.11: Sub-sampling of a 2 cm-thick sample slide using cylindrical vials. The latter collect pre-defined volume samples parallel to the long axis of the core in a top to bottom direction, which enables the calculation of the water content, and thus dry and wet bulk density, respectively.*

Subsampling for geochemical, pollen and diatom analyses were carried out at consistent intervals of 16 cm on the composite core (Fig. 4.5.11) after core correlation and splicing was performed based on visual inspection and XRF data (Chapter 4.4.3). Aliquots of the subsamples were distributed to the Ohrid science community for further analytical work (Fig. 4.5.12).

**Ohrid core correlation and splicing**

Core correlation and splicing of core data obtained from neighbouring bore holes is a critical and essential task to improve the data quality, which is often compromised due to spotty and incomplete core recovery. Simply speaking, not every core retrieved during a drill run exhibits a full recovery, which requires drilling a Hole-B (and sometimes even a Hole-C) close to the original hole of a particular site to fill a particular data gap over drill depth.

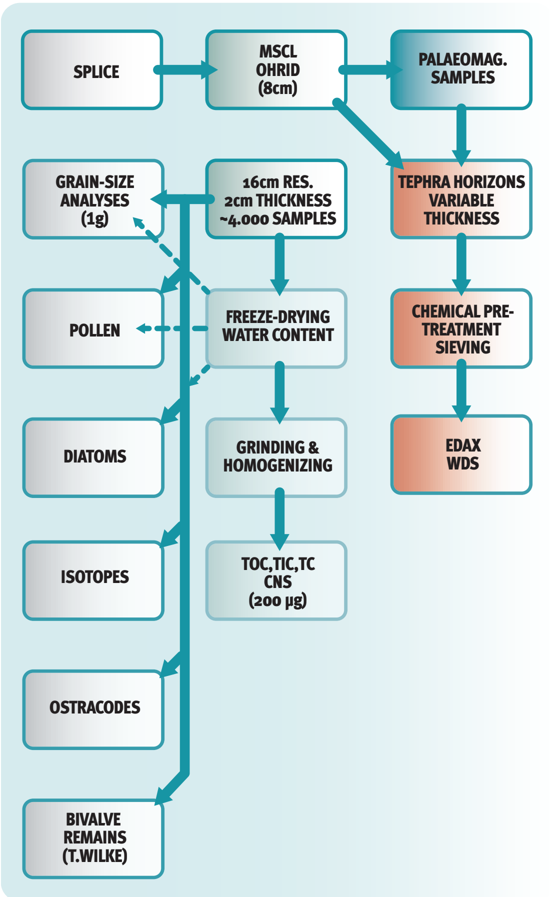


*Fig. 4.5.12: Specific analyses and sampling workflow for the Lake Ohrid expedition. Sub-sequent to the subsampling, the working halves were shipped to Bremen Core Repository for core curation.*

Two standard software applications used in academia to showcase and feature data from the various drill holes are CORELYZER and CORRELATOR. The latter software package allows fetching various data sets obtained in a borehole, placing them on a world wide web-based server, and cross correlate them into a 'spliced' composite-like data profile. The program processes images or any other data (magnetic susceptibility; GRAPE, XRF core scanning data). The splicing itself is based on the idea to match data of a certain kind (e.g., GRAPE or Magnetic Susceptibility) downhole as they can be obtained between two or three drilled holes.

For the long core from the central part of Lake Ohrid (DEEP site), core correlation and splicing were carried out in two steps. First, a preliminary composite profile (splice) was established by using the magnetic susceptibility data, which was measured onsite at Lake Ohrid over an integral of 8 cm in 2 cm steps. The cores of this preliminary composite profile were subsequently processed using the described workflow (4.5.10). Information from the visual core descriptions and the XRF core scanner data was then compiled to establish a refined, final core correlation and composite profile.

### 4.5.3 Core Correlation Software

ICDP lacustrine drilling projects mostly target paleoclimatic and environmental topics typically covering young Quaternary times in high-sedimentation rate regimes (>100 m/my). The combination of short time periods of interest and high sedimentation rates ask for a robust sampling strategy for the various disciplines as well as accurate depths calculations and core depths correlation.

Where multiple boreholes at one drill site are available, a **composite profile/splice record** consisting of the overlapping core segments from the individual boreholes should be created at first (Supplement 6). Afterwards, sampling can be carried out at a regular interval on the final composite record. By applying this sampling strategy, redundant sampling of core sections outside the composite profile/splice record is avoided.

Figure 4.5.13 depicts a detailed 'road map' for an optimized workflow for lake sediment drilling campaigns based on laboratory work on cores from Lake Ohrid. The cores were processed at the University of Cologne (Germany) and detailed information about, e.g., core correlation, can be found in Francke et al. (2016). To get familiar with the software packages mentioned in Fig. 4.5.13, OSG holds a training course on mDIS, 2 – 6 months ahead of the field campaign. For the open-source software packages 'CORELYZER' (real-time core description) and 'CORRELATOR' (stratigraphic correlation), which are recommended for the 'splicing' method, OSG recommends retrieving instructional videos and manuals from the homepage of the CSD Facility: http://csdco.umn.edu/resources/software.

**Core and Data Handling**

Core processing and data management in a science lab build on information obtained in the field, such as the core and section inventory, field depth measurements and on-site analyses such as MSCL (Multi Sensor Core Logger) data recorded at low resolution on whole cores.

MSCL data of magnetic susceptibility and/or bulk density are applied for core correlation using the software packages CORELYZER/CORRELATOR (see below).

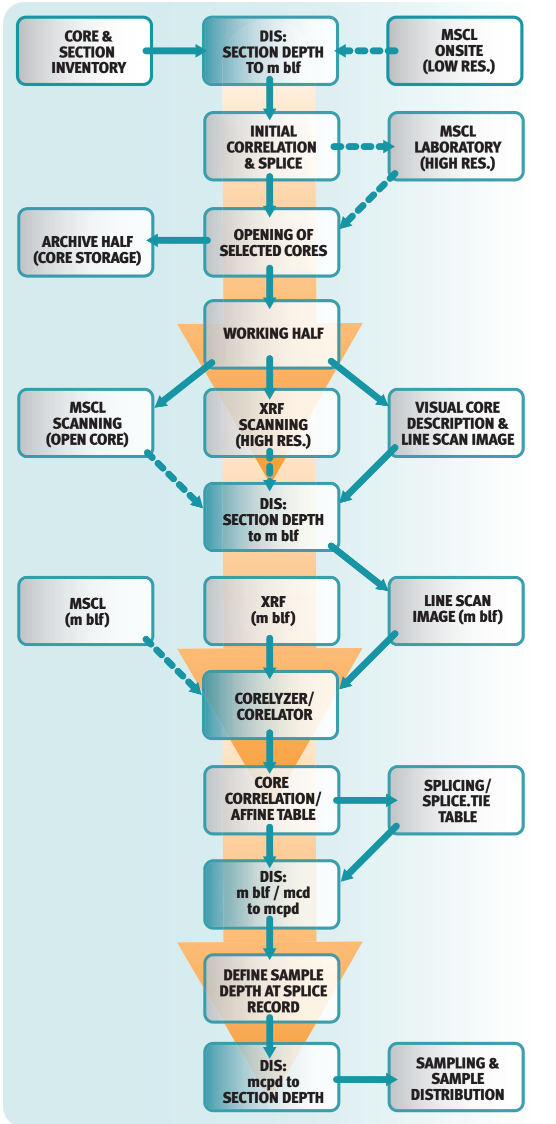


*Fig. 4.5.13: Schematic workflow for the laboratory work and data management for lake drilling projects (mblf: meters below lake floor, mcd: meters corrected depth, mcpd: meters composite depth). The workflow is adopted using the workflow applied for Lake Ohrid data using the old DIS data management tool. The new workflow is work in progress.*

Core correlation and splicing are ideally accomplished in the field, in order to detect possible gaps in the recovered sediment succession and to improve the drilling strategy while drilling. Further, the preliminary splice record can support core processing in the science lab by reducing the number of core sections to be processed. Core sections of this preliminary splice record can be selected for core processing, which shall routinely encompass:

- High-resolution (1-2 cm) MSCL logging and/or CT-scanning on whole-round (‘unrolled”) cores
- Core splitting
- Surface cleaning of the core (working and archive) halves
- High-resolution line-scan imaging of individual core sections
- Visual Core Description (VCD) and smear slide analyses
- XRF (X-ray fluorescence scanning) and high-resolution MSCL logging on split core halves

**Core correlation, splicing, sub-sampling**
Before sub-sampling begins, the final core correlation and splicing shall be carried out on the basis of the lithological information from visual core descriptions in conjunction with high-resolution XRF (or other equivalent) core scanning data (cf. Fig. 4.5.14). The splicing itself is based on the idea to match data of a certain kind (e.g., XRF; RGB; etc.), when obtained between two or three adjacent drilled holes.

CORRELATOR/CORELYZER are used in academia to showcase and feature data from the various drill holes and allow collecting various data sets obtained in a borehole and to cross-correlate them into a ‘spliced’ composite-like data profile (Figs. 4.5.14 and 4.5.15). This can include images depicted with CORELYZER or any other data, i.e., magnetic susceptibility, GRAPE, XRF, showcased with, both, CORELYZER and CORRELATOR. CORRELATOR and CORELYZER can be used in concert and allow a direct crosscheck of the established correlation and splice record between the data records and the line-scan images.

A visual correlation between two horizons (such as tephra layers), which can unequivocally be correlated between two boreholes mostly provides more precise results (Fig. 4.5.15) than a comparison of patterns and shapes of certain data, for example from XRF core scanning (Fig. 4.5.14), and is therefore preferable over a data-based correlation. An example for a spliced line scan image is shown in Figure 4.5.16.

Core correlation is commonly carried out from top to bottom of the drilled record and defines the offset of each core run, i.e., the distance a core has to be moved up or down for identifying proper connection (tie) points with the overlying core from the other/adjacent borehole(s). Offsets can be either negative (core shifts upwards) or positive (core shifts downwards). Due to gas expansion and pressure release of the overlying formation, core runs frequently achieve more than 100% recovery resulting in positive offsets for most of the core runs, and thus, in an elongation of the splice record compared to the original boreholes. On the basis of the defined offsets, the original mblf measurements are commonly converted into the mcd (meters corrected depth) (see Supplements S6, S7).

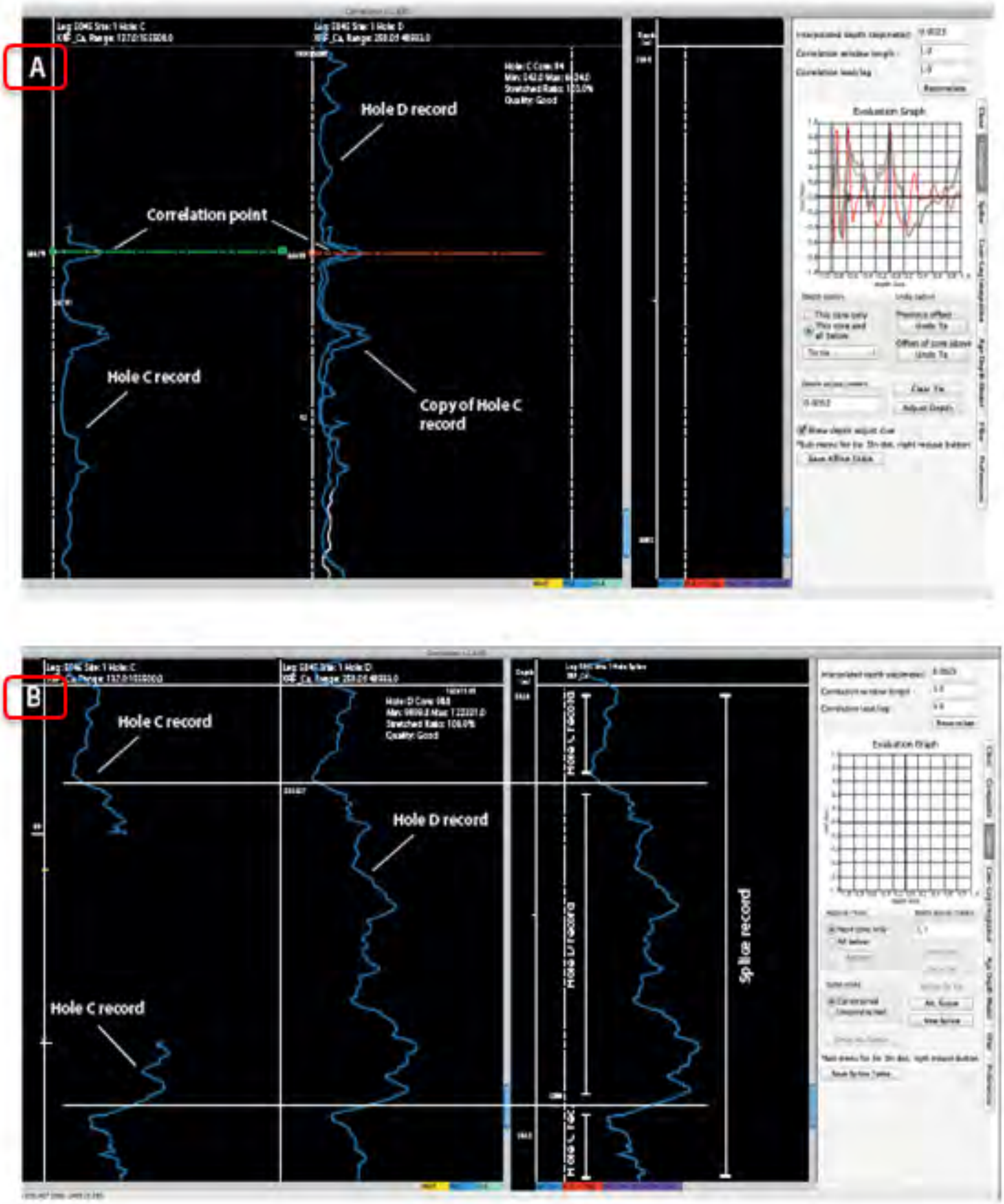


*Fig. 4.5.14 The CORRELATOR software package is commonly used by Earth scientists for visual drill core description and data composition.* ***A:*** *Core correlation using high-resolution XRF core scanning data (Ca=calcium). The data were filtered using the Gaussian filter as provided by the software package. Two representative peaks in the Ca-counts at ~246.8 mblf were used as correlation point between core runs from Hole C (left panel) and Hole D (right panel).* ***B:*** *After core correlation, the individual core runs can be combined to a continuous splice record (right panel) by using intervals from Hole C (left panel) and Hole D (middle panel). The horizontal lines mark the correlated horizons between Holes C and D and the splice point in the splice records, respectively*

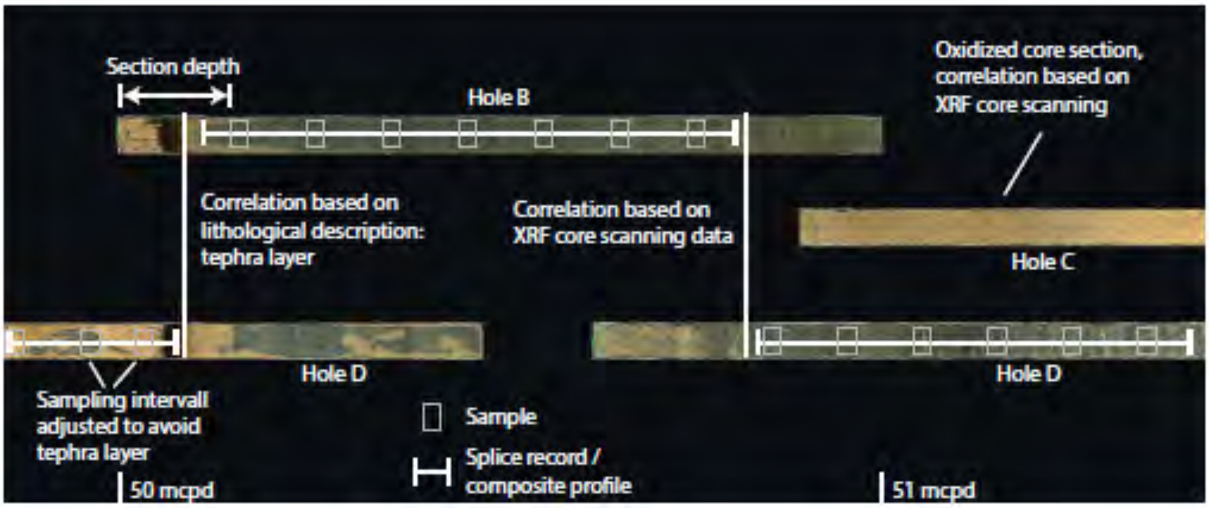


*Fig. 4.5.15: The CORELYZER tool allows for core correlation on data obtained in adjacent Holes B and D. In the case of Lake Ohrid, core correlation was performed using lithological information (tephra layer/volcano-stratigraphy) and information derived from correlating high-resolution XRF scanning data loaded into the CORRELATOR software package. Marked are the 'splice record' and the 'samples', which were taken from the splice record on a regular interval. Special care ought to be taken regarding the various depth scales involved.*

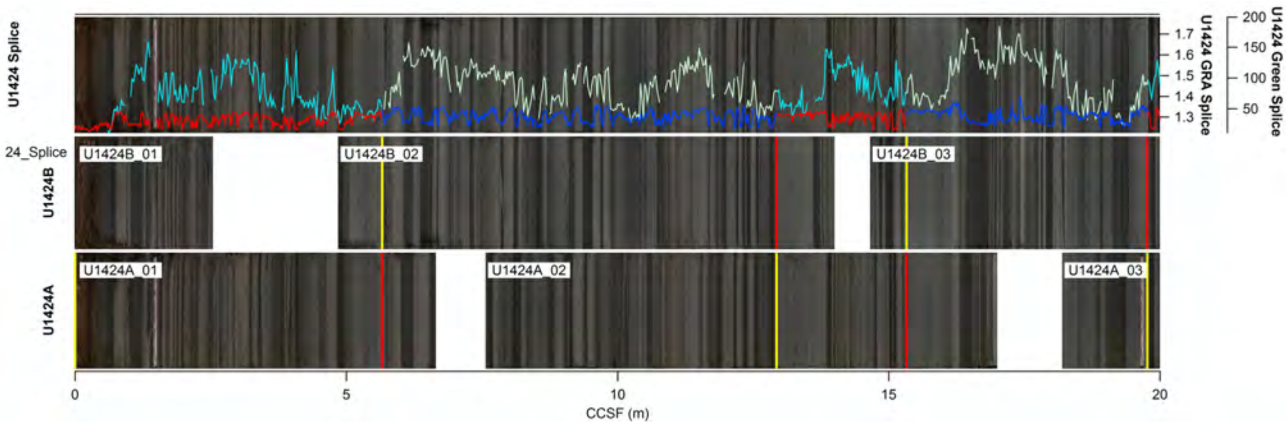


*Fig. 4.5.16: Spliced line-scan images produced on cores from Hole-A -and- B during IODP Exp 346 overlaid by corresponding physical property data (GRAPE and RGB) for the top 20 mbsf. Note that both images and data from corresponding holes are computed into a scaled composite profile based on splice and offset (i.e. 'affine") tables, which are an essential output produced with the CORELYZER and CORRELATOR applications.*

After defining the splice record, i.e., the respective core intervals required to obtaining a continuous sediment profile, the mblf and mcd measurements are re-calculated to mcpd (meters composite depth). Information about offsets and splice ties are saved by the CORRELATOR software as so-called Affine and Splice-Tie tables, respectively. The quality of all approaches is dependent on the correct data input from someone who knows how to apply the CORRELATOR software to produce 'splice' and 'off-set' tables (Fig. 4.5.16). Upon retrieving such tables from the various databases, self-standing macros based on time series analysis software (IGOOR PRO) allow the trained user to splice and overlay all sorts of data sets in a computed and scaled form.

If an unambiguous core correlation was not possible on the basis of the selected core sections from the preliminary splice record, additional core segments from the respective sediment depth of additional boreholes can be split, likewise analyzed and included into the composite profile. In order to optimize the laboratory capacities, XRF and MSCL core scanning is potentially not conducted on the core sections excluded from the splice record, however, splitting and VCD is.

After core correlation and splicing has been performed to a level of agreeable satisfaction a regular subsampling interval (e.g., for geochemical, pollen and diatom analyses) can now be defined for the splice record and corresponding depth (in mcpd scale) of each individual sample (Fig. 4.5.14). For the laboratory work, mcpd is re-calculated into section depth (Fig. 4.5.15). For this purpose, the respective composite depths in mcpd of each individual sample can be imported to the mDIS database. Thereby, it is highly recommended to crosscheck the position of each individual sample in the splice record, e.g., by using the CORELYZER tool, in order to avoid event layers such as tephra layers or MWD (Mass Wasting Deposits) and/or section boundaries during the sampling.

**Field Logging Workflow**

1. Input/Check of core-section data into the mDIS including measurements logged on the mblf (meter below lake floor) scale
2. Printing field Core/Section labels to identify cores and sections using IGSN, core/section number (combined-ID) and possibly sections top-bottom depths (mblf)/drillers depths. The depths are likely to change, so new labels are likely added in the lab
3. Create initial 'Core Correlation' while drilling by using low-resolution MSCL data in order to avoid drill gaps; creation of preliminary composite profile/splice record

**Laboratory Workflow**

4. Optional (depending on core retrieval situation): Re-do the MSCL measurements at high-resolution (cm to mm scale) and/or obtain CT-Scanner data on whole-round core sections
5. Core Section Opening: if more than enough core material is available consider splitting selected core sections of the preliminary composite profile first
6. Possibly, yet very carefully, 'clean' and prepare the surface of the core material prior to core section imaging and other scanning activities; import high resolution line-scan images into mDIS
7. Conduct Visual Core Description (VCD) possibly comprising smear-slide description (sediment) on printed VCD sheets and enter information into the mDIS or conduct VCD directly using PSICAT (open-source software maintained by CSD Facilities)
8. Perform logging of high-resolution XRF (recommended) and/or high-resolution MSCL (optional) data on split core halves
9. Import XRF / other data (MagSus etc.) into CORELYZER for visual inspection including mblf measurements as provided by the mDIS
10. Perform Core-Correlation & Splicing using CORRELATOR/CORELYZER tools
11. Decide whether Core-Correlation requires analyzing additional core sections (if yes, go back to Topic 7 and continue from there)
12. CORRELATOR tool: AFFINE & SPLICE tables
13. AFFINE table contains and defines the OFFSET of individual cores and requires entering it into the mDIS for each core; re-calculation of mcd via mDIS
14. SPLICE table (incl. TIE POINTS for the splicing) are being produced; used for re-calculation of mcdp (meters composite depth) in mDIS
15. Re-do export of Line-Scan Images & Composite mDIS data (e.g., XRF, MagSus, etc.) to CORELYZER or other visualization software
16. Import SPLICE table into CORELYZER for visual inspection of composite sections and sampling spots

17. Sampling on a predefined sample interval on the final composite profile / splice record with respect to specific event layers (e.g., 'Ash Layer') and section top/end
18. Enter pertinent information of all samples obtained from the core material into the mDIS featuring composite (core) depth (mcpd) and calculated corresponding section depth for laboratory work
19. Prepare a representative 'Downhole-Logging Record Master' (spliced and depth corrected data set from Total Gamma Ray, Mag Sus, and/or FMI/BHTV borehole logs
20. Combine Downhole-Logging and final composite profile for detailed 'Core-Log Integration' studies

The method and techniques outlined and presented in this PRIMER Chapter are 'work-in-progress'. Much of the described methodology is standard procedure during expeditions of the International Ocean Discovery Program, IODP, but not yet for lake-drilling ICDP projects. Here, the procedure will need to be standardized for new ICDP projects allowing for opportunities to further optimize and improve the techniques. This pertains to both, sediment and hard rock drilling campaigns and represents a great opportunity for users to get actively involved and participate in this process of continuous improvements as 'Beta Testers" and power users.

### 4.5.4 Cuttings handling at the drill site

Cuttings generally occur as small rock fragments produced during drilling operations (Fig. 4.5.17). Especially when core samples are unavailable, cuttings are often the only method of getting physical samples of the rock formation for mineralogical, geochemical, and/or physical property analyses. The cuttings handling presented in this section is based on the experience gained on-site during the SAFOD drilling project (San Andreas Fault Observatory at Depth, USA), the DFDP drilling project (Deep Fault Drilling Project, New Zealand), and the NanTroSEIZE drilling project (Nankai Trough Seismogenic Zone Experiment, Japan). It includes examples of workflows on both hard rock and soft sediment material.

#### Collecting and washing cutting samples

Before sampling, the amount (usually 1-4 litre) and the depth range of cutting samples (e.g., every 5, 10 or 50 m drilling advance) are agreed upon. The cuttings-drilling mud mix can then be collected in a bucket at the shale shaker (e.g., SAFOD, Fig. 4.5.18a), or directly at the drilling mud outlet (DFDP, Fig. 4.5.18c).

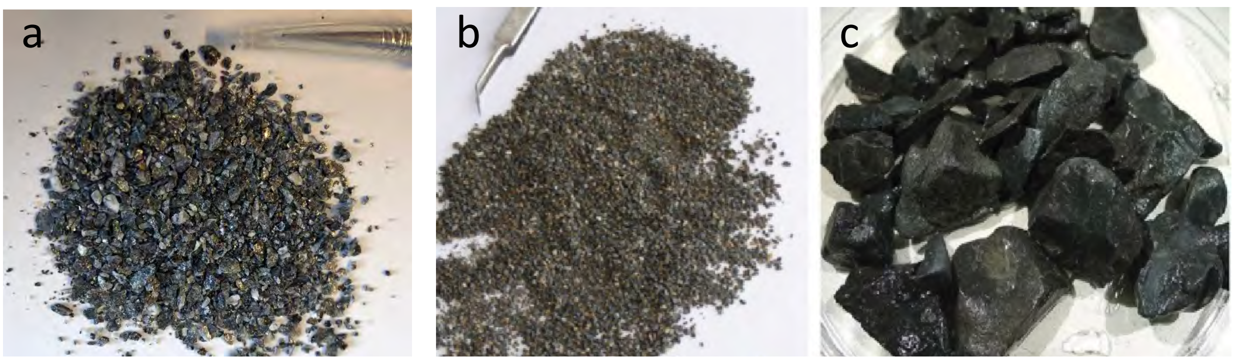


*Fig. 4.5.17(a) cuttings of mica schist taken during the DFDP drilling project in New Zealand, (b), cuttings of a mixture of sand/silt and claystone taken from the SAFOD drilling project in USA, (c) cuttings of silty claystone, siltstone and sandstone taken during the NanTroSEIZE drilling project in Japan (cm scale).*

*Fig. 4.5.18: a) and b) cuttings were separated from the liquids at the shale shaker and later washed with tab water (SAFOD); c) and d) cuttings were collected directly at the drilling mud outlet and rinsed later with tab water (DFDP); e) and f) chip size separation (< 2mm, 1-4 mm, > 4mm) and rinsing of cuttings after collection at the shale shaker (NanTroSEIZE).*

During the NanTroSEIZE Expeditions, 2 – 4 liter of cuttings were collected at the shale shaker per 5 – 10 m drilling advance (e.g., Tobin et al. 2015). The cuttings were routinely separated in an archive portion and a working portion, and only the working portion was used for further analysis.

After collection, the cuttings were washed thoroughly to remove the drilling mud (Fig. 4.5.18b and d-f). Generally, the use of very fine sieves prevents losing fine material such as clay. For a chip size separation (< 2mm, 1-4 mm, > 4mm), several sieves can be used (Fig. 4.5.18e). In these projects, the cuttings were washed with tab water, seawater, or diluted drilling mud fluid. The dilutant should always be discussed beforehand as, for example, deionized water (and eventually also other fluids) may affect the elemental ratios in the cuttings (depending on the rock type). Metal pieces (from the drill bit), plastic or organic material (e.g., cable and nut shells), or cement (from the casing procedure) may be mixed in the cuttings-drilling mud mix, and should be removed as soon as possible with a magnet or trough rinsing.

**Cuttings contaminated with drilling mud**

Drilling mud (or drilling fluid), usually a heavy, viscous fluid mixture of water, clay and polymers, is used to carry the rock cuttings to the surface and to lubricate and cool the drill bit during drilling operations.

It can physically and chemically alter the cuttings, and is therefore the main source of rock contamination. Especially chemicals such as calcium carbonate, sodium chloride or potassium chloride, barium sulfate or hematite are sometimes added to the drilling mud in order to control formation pressure, mud pH, mud viscosity, wellbore stability, or temperature. In fact, all drilling additives hamper the quantification of the true mineral content, especially when clay minerals are present. These chemicals should be washed out as soon as possible using rinsing water. However, any kind of soaking of the cuttings in the cleaning fluid for longer periods should also be avoided.

**Labelling and imaging**

Labelling the cuttings can be handled individually, but should best be adjusted to the core labelling (see above). Photographs can be taken before or after the initial visual description. At the NanTroSEIZE project, cuttings were washed and separated into the different mineralogy before a photograph was taken (Fig. 4.5.19a). At the DFDP drill site, a photograph of the washed cuttings was added to the petrographic description report (Fig. 4.5.19b).

**On-site description**

The initial visual examination of the cuttings usually includes descriptions of:

- the color of the cuttings
- the range and average of the different chip sizes
- the ratio of dispersed grain from disaggregated lithologies (e.g., sand) to cuttings chips
- the induration state of the cuttings
- the cohesion (stickiness) of cuttings
- the abundance of special categories (e.g., wood, coal, large fossils)
- the degree of contamination by metal shards, paint chips, or fragments of casing cement

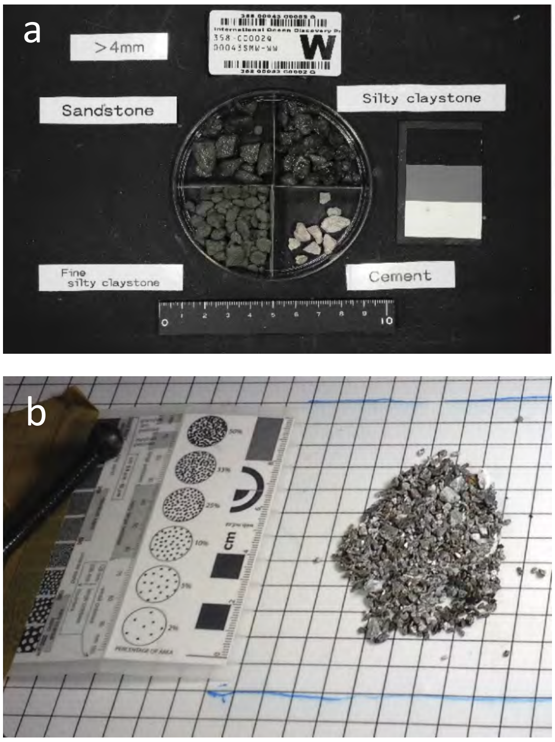


*Fig. 4.5.19: Photographs of a) NanTroSEIZE cuttings (> 4 mm) separated in sandstone, silty claystone, fine silty claystone, and cement (from casing). The label in the upper part shows the expedition, drill site, drill hole, material number, method (solid taken from mud water), and the working portion; b) DFDP cuttings (all grain sizes) with percentage of area, sorting, roundness etc. for later description.*

Examination of the washed cuttings is done visually, with an optical microscope or a binocular, depending on the availability at the drill site.

Descriptions with the petrographic microscope can be done based on:

- grain and mineral composition
- relative abundance of constituents
- average and range of grain size
- grain sorting
- grain roundness

At the DFDP and the SAFOD drill sites, cuttings chips were mostly described based on their mineralogy (mica, serpentine, quartz etc.), whereas at the NanTroSEIZE drillsite, cuttings chips were first separated in sandstone, siltstone, silty claystone. In some soft sediments, the preparation of smear slides can be helpful for visual examination of the mineralogy. They can be prepared from washed and gently crushed chips after grain separation and washing. As lithification of sediments advances with increasing depth, more effort should be directed toward segregation of each interbedded lithology for smear slides (e.g., mudstone, siltstone, fine sandstone, volcanic material). This can be accomplished by hand-picking chips of each lithology. Descriptions using the petrographic microscope are similar to the visual description. Depending on the lithology, thin sections may be more useful for this description. The cutting chips need to be impregnated with epoxy prior to the preparation of the thin section.

**Final remarks**

Cutting samples are valuable in that they provide a direct insight into the nature of drilled formations but their composition can be affected by several biasing effects related to the retrieval procedure, including:

1. chemical contamination of the cuttings due to drill mud interferences (e.g., infiltration of drilling fluid or precipitation of unknown phases);
2. mixing of the cuttings with other borehole material, thus containing grains from above the depth to which the sample is associated with based on drilling mud circulation velocity;
3. disaggregation of poorly consolidated sediment chips leading to preferential survival of certain lithologies in the cuttings;
4. physical drilling artefacts such as polished surfaces on cuttings chips due to drill friction (bit metamorphosis).

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Zoback M., Hickman S., Ellsworth W., 2011. Scientific drilling into the San Andreas Fault Zone –an overview of SAFOD's first five years. Sci. Drill. 11, 14-28

**Further readings**

CSD Facility, University of Minnesota: Lab Procedures - LacCore Standard Operating Procedures

MARUM, University of Bremen: Core storage and sampling - BCR Practices and Procedures

DOSECC, Lake and Marine Drilling Planning and Operations Manual

IODP, Texas A&M University: IODP Core Lab and Sample Handling Cookbook

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CHAPTER 4.6

# Downhole Logging

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Downhole logging is the continuous measurement of one or more parameters along a borehole under in-situ conditions. Synonymously used terms are: well logging, borehole logging, just 'logging', wireline logging or geophysical logging, although the latter two are subdisciplines of downhole logging.

Downhole logging is a powerful tool to gain continuous, in-situ measured, and highly depth-reliable data of various physical, chemical and structural parameters of the borehole surrounding formations: natural radioactivity, electrical resistivity, self potential, density, sonic wave velocity, porosity, magnetic field & susceptibility, borehole wall images, concentration of elements and more. No sonde is able to directly measure the desired parameter but the measuring setup of actually every sonde always measures a voltage, which is translated to a logging parameter via calibration. These calibrations are truly valid only under specific assumptions of the measurement conditions. Deviations from these conditions can cause the sonde readings to differ from the real values of a formation. Especially in the oil & gas prospection huge efforts have been put into correcting boreholes for these effects but which can only be applied in formations similar to those of typical oil & gas sedimentary environments.

A few sonde types measure basic physical parameters of electric resistivity, magnetic field and susceptibility, gamma radiation, and elastic wave propagation. Other parameters are derived from these by interpretation and not by calibration, e.g., porosity, permeability, density, elemental concentration, gas saturation. The measured data of such interpretative sondes cannot be used one-to-one in other than classical sediment environments (igneous rocks, metamorphic formations etc.).

The individual log responses are determined by the properties of diverse parameters of the measured formation, which again are dictated by rock type, mineral composition, fabric, fluid filling, but also temperature, pore pressure, hydraulic pressure, stress, outer electric and magnetic field, geometrical orientation with respect to the sensor array, etc. A log value therefore characterizes the entirety of rock composition and the, mostly transient, in-situ conditions of the measured material:

formation = rock + in-situ conditions

Lab measurements of a core from the same depth that is, of course, detached from both its originating rock unit and the in-situ conditions probably show significantly different values than the downhole log.

Wireline logging is the most commonly used downhole logging method, where the downhole measuring instruments, the logging sondes (also: logging tools) are run inside the borehole on a special logging cable. Because of its most accurate and closest-to-reality depth determination in a borehole it provides the depth reference for any driller-depth-derived depth, e.g., for the correction of core, cuttings, and mud sample depth, but also for depth-truthing of surface seismic data. Wireline logging data can bridge gaps in core data profiles in case of core loss.

Apart from these applications related to cores, cuttings and mud samples, downhole logging data on its own are mostly used for so-called formation evaluation, lithological classification, structural mapping and many other geological interpretations. They are necessary for the in-situ identification and characterization of discrete borehole features like fluid and fracture systems, ore bearing zones, and are essential for the investigation of the in-situ stress field. Special wireline tools are also capable of extracting fluid and rock samples from discrete localized zones of interest, so-called downhole sampling.

Finally, apart from these scientific purposes, wireline logging is an indispensable support of drilling operations delivering necessary information about the borehole geometry and orientation, the drilling mud condition, required cement volumes and later its quality, casing corrosion, and many more.

**Logging basics**
Downhole logs are acquired with various types of logging sondes, containing one or more sensors for different parameters. With the wireline logging method, the downhole tools (logging sondes) are mechanically and electrically connected to a downhole logging cable (hence the term wireline), which is lowered into and pulled out by a special wireline logging winch at surface. The cable holds the weight of the sonde and contains electrical wires for power supply and telemetry (data transmission between sonde and surface and vice versa), see Figure 4.6.1.

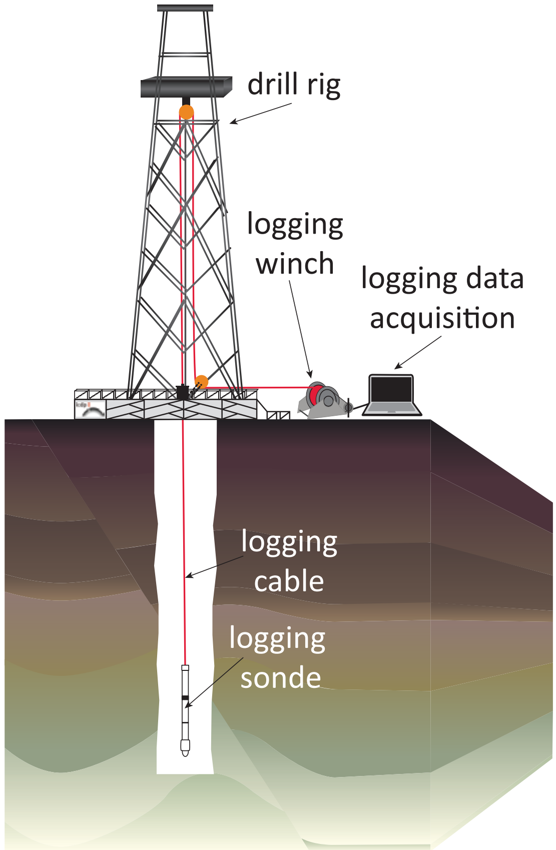


*Fig. 4.6.1: Downhole logging scheme.*

A logging winch has a rotatable lead-out of the cable wires allowing to continuously measure while the winch drum is revolving, i.e., moving the sonde up or down in the borehole when running a log. The electric lines coming from the winch are connected to an attendant data acquisition system, consisting basically of an interface panel for power supply and sonde communication and a computer for sonde control and data recording. Some sondes can be combined in sonde strings to be logged together in one run in order to reduce the number of logging runs necessary to acquire the desired parameters (Fig. 4.6.2).

The wireline depth is determined by directly measuring the cable motion with a counter-wheel as it unspools off the winch drum. Stretching of the cable due to the increasing weight of the cable the deeper the sonde runs into the borehole is actually measured. Therefore, the wireline logging depth is regarded to be the most accurate and closest-to-reality depth measurement in a borehole.

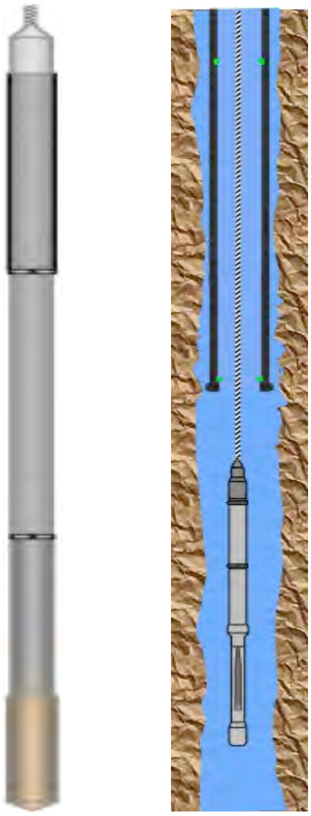

*Fig. 4.6.2: Sketch of a sonde combination comprising total gamma ray, spectrum gamma ray and magnetic susceptibility, from top to bottom (left). A logging sonde is run through a coring drill string and the bit after the inner core barrel has been pulled out (right).*

Most downhole logging is performed inside open borehole sections, open hole logging, i.e., without a steel or plastic pipe protecting the borehole. Some methods can also measure through a steel tube, like inside a casing or drill pipe (e.g., gamma radiation, density) but need to be corrected for the absorption by the steel.

It is recommendable and a common practice that before wireline logging commences to flush the hole clean of possible formation fluid contaminations and larger solid particles by circulating the drill mud for several cycles. Understandably this will be avoided or at least minimized if the detection of fluid bearing zones in low permeable rocks is of high priority. The drill pipe and bit will be tripped out of hole to allow the wireline sondes to be run in for logging. In case of wireline core drilling it is usually possible to trip out the drill string not entirely, but only partially, until the bit is positioned just at the top of the desired logging interval and the sonde is run down through the drill pipe and through the coring bit into the open hole section below. This time-saving method is the standard procedure for lake drillings (Fig. 4.6.2).

**Sonde size**

Logging sondes come in a variety of sizes (diameters). They can be separated into two groups: (i) standard sized sondes and (ii) slimhole sondes; but there is no strict definition. Commonly sondes with a diameter less than about 60 mm are regarded to be slimhole sondes, whereas standard sondes have a diameter of 86 mm ($3^3/_8$") and up. There are intermediate sondes with a diameter of around 60 to 75 mm. Obviously big sondes cannot be run in a slim borehole because they simply do not fit into the hole, while slim sondes placed in a very wide borehole are usually not recommended either. Many slimhole sondes lose their performance in holes that are too wide. They perform best in borehole diameters less than 130 mm (PQ, HQ, NQ).

**Non-wireline downhole logging**

Besides running logging sondes on a wireline there are several other methods to deploy logging sondes in a borehole. These methods were developed to enable downhole logging also under hole conditions adverse to wireline logging. Obstacles like partially blocked hole sections (large-scale wall collapse, swelling formation, local bridging) or borehole trajectories strongly deviating from vertical (> 45°) make the use of logging sondes on a wireline risky, extremely difficult and time-consuming or even impossible. Nowadays popular and very successful in oil & gas exploration are logging tools integrated into the drill string (logging while drilling, LWD) but which are yet unavailable for slim hole sizes. Other sonde deployment methods mount wireline sondes either to a regular drill string and then measure during an additional full round trip of the string or mount wireline sondes to a coiled tubing drill string (coiled-tubing conveyed logging). The necessary winch drums are very big and their expensive application adds to the normal wireline costs.

For small to medium scale drillings (e.g., HQ, PQ) the method of running autonomous memory logging sondes on the drill string during its last trip-out (logging-while-tripping, LWT), see Figure 4.6.3, was established as a robust and reliable way to gain a basic set of downhole parameters under adverse hole conditions. The memory sondes are thrown into a drill string, sink down and land near the drill bit either with the entire sonde string staying inside the pipes or partially sticking out through the core bit into the open hole. The LWT depth is determined by measuring the motion of the drill pipe. Although the trip-out happens in steps and even with varying speed the achievable depth accuracy is comparable with that of wireline logging but other than the wireline depth the LWT depth determination is not independent of the driller's depth.

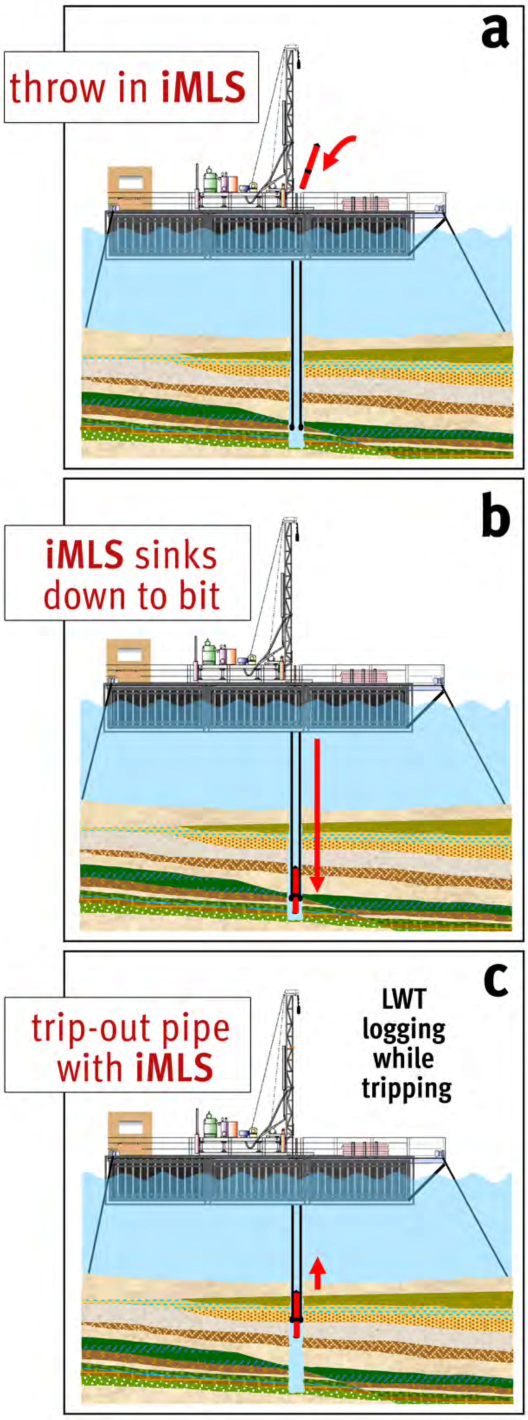


*Fig. 4.6.3: Principle of Logging While Tripping (LWT) with ICDP memory logging sondes (iMLS).*

**Developing a logging plan**

In an early planning stage of a drilling project, it is possible to include logging demands such as limitations on hole size, hole deviation, drilling method, drill mud type, logging section length etc. into the drilling plan to provide the best possible logging conditions. This is usually the case in projects where downhole logging has a high priority (Case A). In other projects logging has to be adjusted to the given borehole conditions (Case B). Furthermore, in an advancing project technical or financial reasons may cause significant changes to the original drilling plan and thus suddenly impose very different conditions for downhole logging, in the worst case even exclude borehole measurements.

Scientific questions for logging in a project will usually be defined by the whole project team. A list of borehole parameters necessary to answer these questions (see Tab. 4.6.1) has to be derived by a group of 'logging specialists' composed of scientists who ultimately want to work with the downhole logging data. The group chooses a responsible leading scientist as logging manager for the time of the entire project who coordinates planning, on-site oversight, data analysis and publishing.

This logging manager with backing support from his logging group identifies not only downhole methods (Tab. 4.6.1) for scientific purposes but also methods that support the project at large (e.g., depth correlation, lithology reconstruction, drilling technical support etc.). Furthermore, a classification scheme is needed which logging method is appropriate for the anticipated borehole conditions: hole size, pressure, temperature, high/low electrical resistivity, soft/hard formation etc.. A form, to which the logging manager can refer, can be found on the ICDP web.

In Case A requirements for the drilling plan are listed to gain best possible borehole conditions for logging including: drilling location (accessibility), hole size, hole deviation, mud type, mud weight, cooling rates by mud circulation, length of logging sections and frequency of logging runs.

In Case B the drilling scheme and the plan for the mud system are given, resulting restrictions for the downhole logging:

- hole size
- hole deviation
- mud type
- mud weight
- expected temperature and pressure
- achievable cooling by mud circulation
- available time for each logging session or single runs.

Another constrain limiting or even prohibiting the use of density, porosity, and some elemental sondes are restrictions to deployment and cross-border shipment of instruments with nuclear sources.

It is recommended to create at least two logging scenarios, one with the maximum desired amount of logging and one with a minimum, indispensable amount of logging runs. Reality will lie somewhere in-between. A general minimum set of logs could be like this:

- caliper (preferably 4-arm oriented)
- borehole orientation (azimuth & deviation, at least the deviation)
- total natural GR (gamma ray)
- fluid temperature (preferably together with fluid resistivity)

This set may be extended by other tools depending on the scientific focus of the project, including:

- magnetic susceptibility
- sonic velocity
- formation resistivity
- natural gamma spectrum
- formation density

A well-prepared plan of reasonably prioritized downhole measurements will provide a sound base for discussions in the early stage of the project planning. This prioritized logging plan is also useful as decision support later during drilling if project delays reduce the effective time available for logging. The question which logging service providers and which tools are available for the given borehole conditions needs to be addressed during an early project stage. A contingency plan with options of equivalent and alternative sondes and/or providers is recommendable. We recommend to consult with Operational Support Group (OSG) or other trustworthy experts, who do not have a commercial interest in your project.

Logging sondes and other logging equipment must be technically appropriate for the anticipated

- hole size
- core size (=inner diameter of the bit)
- bit type
- mud type
- temperature & pressure
- demands on cable type & length, and cable head weak point
- necessary winch type (min/max speed, max. force)
- local transport possibilities/limitations
- electric power supply
- available space for logging equipment
- special demands on the data acquisition

Once the decision on the logging provider is made, a representative of the logging provider should participate in preparatory and kick-off meetings of the drilling project. An early involvement avoids unnecessary misunderstandings and double work on both sides and hence will save time and money (and nerves).

A logging plan must be adjusted to the drilling constraints and has to be self-consistent and cost transparent, flexible enough to encounter delays, sonde drop-outs and even minor budget cutbacks (Fig. 4.6.4). Of course, all logging group members must eventually agree with the plan, let alone to avoid cumbersome discussions when they are most disturbing during any kind of crisis. The plan has to consider the time necessary for logging of all sondes with their commonly very different logging speeds including the times necessary to run in the sondes until reaching the actual logging section and out again (Table 4.6.2). All logging is carried out while moving upwards, except for the temperature log, which is measured downwards. At least one check log (repeat log/run) of each sonde typically over a section of 30 to 50 m length should be included as well. These repeat logs serve to verify the reproducibility of the tool readings.

Finally, a mitigation procedure for a lost in-hole scenario completes a logging plan. This is needed because a lost sonde that cannot be fished (retrieved from the borehole) will cause severe consequences: 1) The borehole will be inaccessible below the sonde stuck depth and therefore probably unavailable for subsequent downhole experiments; 2) The logging service provider might not be able to continue logging in other boreholes of the project because essential equipment components might be lost with the stuck sonde.

Questions of such a scenario comprise:

- Can the sonde(s) be fished?
- Does the cable head have a 'fishing neck'?
- Is appropriate fishing equipment available? Within what time frame?
- Are fishing guidelines available?

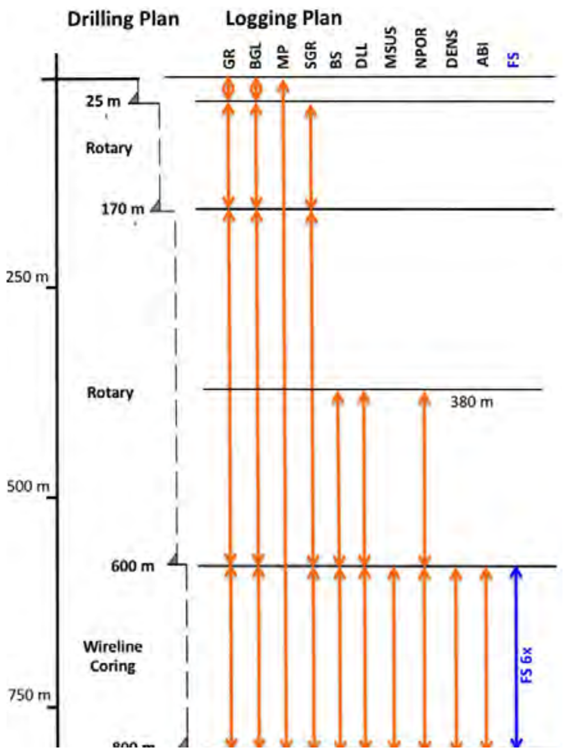

*Fig. 4.6.4: Example of an optimized logging plan. GR: total gamma ray, BGL: borehole geometry, MP: mud parameter, SGR: spectrum gamma ray, BS: sonic, MSUS: magnetic susceptibility, NPOR: neutron porosity, DENS: density, ABI: acoustic imager, FS: fluid sampler*

A logging contract/agreement between the project and each logging provider has to lay down the responsibilities, liabilities and duties of the project on one side and the logging provider(s) on the other side. The most important components are:

- the lost-in-hole case
- explicit naming of the responsible persons and decision makers
- terms for data handling/processing and data ownership
- technical requirements for the logging operations
- cancellation terms
- payment terms

**Health and Safety Measures**

A Logging Safety Instruction including the emergency & escape plan according to the general regulations of the drilling project must be held on-site before any logging campaign begins. All personnel involved have to study, understand, and sign these logging safety regulations. Any personnel at the site has to be instructed before getting to work. Safety equipment such as hard hats, glasses, gloves and shoes are compulsory for all logging activities. Several other restrictions on safety measures may apply depending on national laws, drilling contractor regulations or other. Generally, all logging work is limited to working shifts of 12 hours at maximum.

The risk of blowouts of dangerous fluids and gases needs to be estimated because the standstill of mud circulation during downhole logging time might promote rise and outflow of gas. Regular information exchange with the drilling engineer are critical and safety measures such as gas detectors for several gas types need to be installed in such projects.

**Possible restrictions on logging sondes**

Hole Size

Not all sonde types (measured parameters) are available for slimhole, normal sized and big boreholes. Consider that if one provider cannot offer the desired sonde another might be able to do so. Always ask for a drilling scheme with explicitly provided hole diameter(s). Do not rely on hole type names like HQ, NQ, etc.. A drilling that delivers an HQ core not necessarily has to drill an HQ borehole (≈ 96 mm) but could drill a far wider size (> 200 mm).

Hole Deviation

A high borehole inclination can prevent sondes from slipping freely down the hole, in general the maximum angle is about 45-50 degrees (with otherwise normal hole conditions). If strong hole enlargements are abundant, sondes may get blocked already at an inclination of 5-10 degrees. Some sondes with mechanical sensors can be used only within a certain inclination range, such as seismometer and geophone sondes or tilt-meters.

Drill Bit Type

In case the logging sondes will be run through a core drill string into the open borehole section (i.e., lake drillings), the core bit has to have a shape that allows the wireline sonde to safely re-enter the drill string while coming up. Especially in the case of a wide borehole but yet a small core size, a thick core bit with high cutting blocks can catch the sonde head while trying to re-enter the drill string and prohibit a safe exiting of the probe from the hole. In such a case the loss of the sonde is very likely.

Mud Type

Resistivity sondes of the laterolog type cannot be used in oil-based muds and in air- or foam-filled holes. Therefore, choose an induction type resistivity sonde instead. Mud constituents can erroneously affect sonde readings, e.g., many water muds (e.g., bentonite) contain potassium, and hence add a contribution to the measurement of the natural gamma spectrum sonde, thus yielding K values that are too high. A very thick mud (high solid contents) will likely obstruct the port of a pressure sensor, clog the cage around a temperature sensor, hinder flowmeters, prohibit downhole fluid sampling, and will reduce (maybe strongly) the quality of acoustic borehole wall images (televiewer).

Mud Weight

The mud weight raises the downhole pressure, which may lead to conditions in the target depth unsuitable for some sondes with low pressure limits. Always make sure the sondes will be used in their given pressure specifications. Do not just rely upon a given depth specification of a sonde.

Temperature and Pressure

Not all sonde types (measured parameters) are available for high temperature and/or pressure, where usually temperature is the most limiting factor. Consider that if one provider cannot offer a high-temperature sonde version another may be able to do so.

**Additional information**

OSG logging equipment such as sondes, their limits and capabilities can be found in Tables 4.6.3 and 4.6.4 and for more details is provided on the ICDP website.

*Table 4.6.1: Overview on parameters and applications of downhole logging sondes.*

| Parameter | Applications | Sonde Method Name | Examples of typical Sonde Mnemonics |
|---|---|---|---|
| borehole wall features | borehole condition/stability, structural features, bedding/ lamination, breakouts, stress field orientation by breakout orientation & drilling induced fractures | Acoustic Imager (Televiewer) | BHTV, ABI, UBI, CBIL, CAST, FAC |
| | like above but stress field orient. only by induced vertical fractures | Electric Imager | FMS, FMI, STAR, EMI |
| | like Acoustic Imager but works only in clear water not in drill mud | Optical Imager | OPTICAL SCANNER |
| | structural features, bedding/ lamination, stress field orientation by breakout direction (multiple runs) | Dipmeter | DIP, SHDT, HDT |
| caliper, borehole geometry/ orientation | borehole condition: size, shape, volume, orientation/direction, path, stress field orientation by breakout direction (multiple runs), technical hole inspection | Caliper, Oriented Caliper, Geometry Tool, Gyro Survey | BGL, CAL-ORI, DIP |
| density | lithostratigraphy, core-log correlation, derived: porosity, mineral identification | Density | LDT, DENS, FDC |
| electrical resistivity | lithostratigraphy, conduction type metallic/electrolytic, fluid invasion, porosity, ground truthing of magnetotelluric & electromagnetic models | Laterolog Resistivity | DLL, LL3 |
| | | Induction Resistivity | DIL, IND |
| | | Micro-Resistivity | MSFL, MRS |
| element content | Semi-quantitative determination of Ba, C, Ca, Cl, Gd, K, Na, S, Si, Al, Cu, Fe, Ni, Mg, Mn, Ti for litho-geochemistry | Geochemical or Elemental Sonde | LithoScanner, ECS, GLT |
| gas saturation | reservoir characterization | Reservoir Parameters | RST |
| gravity | large scale density profile (even in cased holes), ground truthing of gravimetric models | Borehole Gravity Meter | BHG |
| magnetic suscepti-bility | core-log depth correlation, depositional stratigraphy, inter- & intra lava flow differentiation, lost-in-hole metal detection, lithology | Sus-Log | MS, MSUS, MagSUS |
| magnetic field | profile of the magnetic field vector | Magnetometer | BHM |
| | total magnetic field magnitude | Borehole Geometry | DIP, BGL, CAL-ORI, imagers |
| natural radioac-tivity | lithostratigraphy, shale volume, core-log depth correlation | Total Gamma Ray | GR |
| | U, Th & K contents, litho-stratigraphy, heat production, fracture localization | Natural Gamma Spectrum | SGR, NGR, NGS, GRS |

| | | | |
|---|---|---|---|
| porosity | reservoir characteristics, fracture/flow zones, lithology, texture, compaction | Neutron Porosity | NPOR, PORO |
| | | Nuclear Magnetic Resonance | NMR, CMR |
| sonic velocity | lithostratigraphy, compaction, reservoir characteristics, fracture/flow zones localization, seismic ground truthing | Sonic | BS, BCS, DSI |
| mud paramet-ers: tempe-rature, pre-ssure, resis-tivity, flow | fracture and flow zones localization & characterization, fluid regime, deep fluid circulation patterns, heat flow, fluid flow, hydraulic transmissivity & permeability, mud density, cement head localization, gas detection, | Mud Parameter, Temperature, Salinity Flowmeter | TEMP, MP TEMPSAL, MRES, FLOW, FM, MPFM, DIGISCOPE |
| fluid samples | fluid samples (liquid and gas) often combined with hydraulic tests | Fluid Sampler | PDS, Kuster, RFT |
| rock samples | rock anisotropy, structural analysis, fill core gaps | Sidewall Coring Tools, Formation Sampler | MSCT, CoreVault, CST, MaxCOR, coring gun |

*Table 4.6.2: Typical logging speed of some sonde types and time to log depth sections. Times are exclusive of sonde rig-up time and running in and out to the logging sections.*

| **Sonde** | **Speed m/min** | **Speed ft/hr** | **Time/h 0-500 m** | **Time/h 1000-1500 m** | **Time/h 2500-3000 m** |
|---|---|---|---|---|---|
| Caliper/Geometry | ≈ 13 | < 4000 | 1 | 1.8 | 3 |
| Resistivity | 10-15 | 2000-3000 | 1.2 | 2 | 3.2 |
| Density | 9 | 1800 | 1.3 | 2.1 | 3.3 |
| Porosity (Neutron) | 9 | 1800 | 1.3 | 2.1 | 3.3 |
| Sonic | 7-10 | 1400-2000 | 1.8 | 2.4 | 3.6 |
| MSUS | 8-10 | 1600-2000 | 1.4 | 2.2 | 3.5 |
| Temp/Pressure | 8-12 | 1600-2400 | 3.6 | 6 | 10 |
| GR Spectrum | 2-5 | 400-1000 | 4.8 | 5.7 | 7 |
| Elements Log | 2-4 | 300-600 | 4.8 | 5.7 | 7 |
| Electric Imager | 3-10 | 600-2000 | 3.3 | 4.1 | 5.4 |
| Acoustic Imager | 2-5 | 200-1000 | 4.8 | 5.7 | 7 |
| | | | | | |
| Gravity | 20-30 per day | | - | - | - |
| Fluid Sampler | 1-3 per day | | - | - | - |

## DOWNHOLE LOGGING METHODS

### Borehole Caliper & Geometry

A caliper sonde measures the diameter of the borehole cross section. The standard 4-arm caliper sonde has two perpendicular arm pairs, which are pressed against the borehole wall. Other types are 6-arm and also widespread 3-arm caliper sondes. The latter is unable to univocally describe an oval-shaped borehole cross section.

A combination of a caliper sonde with an orientation device gives an oriented caliper sonde, also called borehole geometry sonde. The spatial orientation determines the borehole's deviation from vertical (DEVI), the direction of this deviation with respect to magnetic north, called hole azimuth HAZI or drift azimuth DAZI, and the orientation of the caliper arms with respect to magnetic north and to a reference marker on the sonde housing. Caliper data are needed for the environmental correction of many other logs. It is mainly wanted for technical purposes like knowing the borehole shape and volume (e.g., before running in casings or to determine the necessary cement volume), and its direction and trajectory to apply directional drilling corrections. Caliper data are also used scientifically e.g., to determine the stress field orientation by measuring the orientation of induced borehole breakouts (BO).

### Natural Gamma Ray

The total gamma ray log (GR) is a measure of the natural radioactivity of the formation (Fig. 4.6.5). It is measured by counting all incident gamma rays (gamma counts). The tool calibration converts the counts into a standardized unit named gamma-API [gAPI]. This log is particularly useful for distinguishing lithology, facies, cyclo-stratigraphic analysis and analysing deposition environments, e.g., to distinguish between sands and shales. This is because sandstones usually contain mainly quartz, whereas clays in shales contain Potassium and adsorbed Uranium and Thorium.

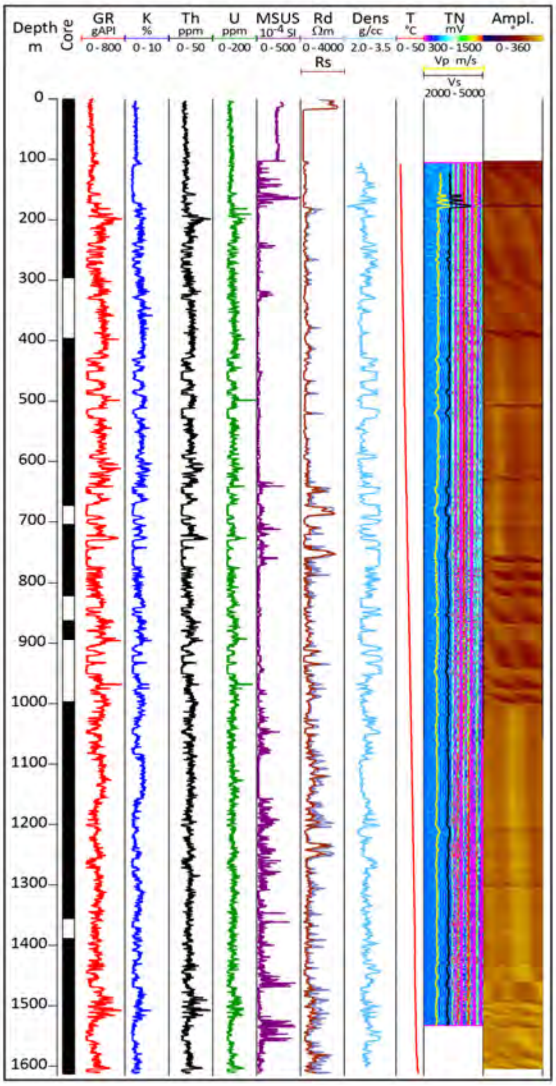


*Fig. 4.6.5: Example of downhole logging data plot. Core recovery (left column; black = core recovery) and a compilation of downhole logs (from left: total natural gamma ray, contents of U, Th, K, magnetic susceptibility, resistivities (Rd and Rs; deep and shallow resistivity, respectively), density, temperature, sonic and amplitude borehole wall image).*

The GR log is the standard log for depth correlation amongst several logging runs as well as between downhole log data and core/cutting data. The total gamma ray sonde records the total radiation coming from the formation whereas the natural gamma spectrum sonde (SGR) delivers the contents of the three main sources of natural radioactivity: potassium ($^{40}K$), thorium ($^{232}Th$) and uranium ($^{238}U$) (Fig. 4.6.5). The sonde measures not only the total counts of the incident gamma rays but a full spectrum of their energies from which a calibrated best-fit algorithm derives the contents of U, Th in parts per million [ppm] and of K in percent [%]. The SGR data are used for e.g., lithostratigraphy construction, determination of heat production, identification of fracture zones, of coal, and estimation of the clay content.

**Sonic**

Sonic sondes determine the velocities (v) of sonic sound waves of the formations (p-waves, s-waves, surface waves (Stoneley); Fig. 4.6.5), which varies depending on lithology, rock texture, porosity, fluid filling, stress and temperature. It is determined by measuring the travel time of sonic pulses between sonic transmitters and at least two, often more, acoustic receivers. The unit of the velocity is meters per second [m/s]. Especially in oil and gas reservoir logging it is common to give the reciprocal velocity, typically in [µs/m], called slowness. Potentially confusing it is also called interval transit time or delta t ($\Delta t$) but with the same unit as the slowness. The sonic velocity is used for stratigraphic correlation, identification of compaction of lithologies, facies recognition and fracture identification and furthermore for ground truthing of surface seismic data and to derive the porosity of a formation. Sonic waveform logs (VDL) and analysis of Stoneley waves are used to localize zones with fractures or other high permeability.

**Density**

A density sonde provides the formation´s bulk density, which is the sum of the solid matrix density (minerals forming the rock) and the density of fluids enclosed in the pore space or other voids (Fig. 4.6.5). The unit of the density is grams per cubic centimetre [$g/cm^3$]. The sonde contains a chemical radioactive source, which emits gamma rays. These are back-scattered by the formation and registered by gamma ray detectors (scintillation crystal) in the sonde. The denser the formation, the more gamma rays are absorbed on their way through the rock and hence less gamma rays reach the detectors. The density is an important parameter for lithostratigraphy construction. It is also used to calculate the porosity of a formation. In conjunction with sonic velocity data it is possible to calculate the acoustic impedance, and to calculate the elastic moduli (i.e. Poisson´s ratio, Young´s modulus; Shear modulus). In addition, the density values are used to estimate the magnitude of the vertical stress.

**Porosity**

The porosity is defined as the ratio of the volume of pore space to the total volume of rock: $\phi = Vol_{pore}/Vol_{total}$ and is usually given in percent [%] or as a fraction from 0 to 1. In this sense it is not an intrinsic physical property of the formation but a geometrical property which can change drastically in a core when it is brought to surface and is released from the confining pressure. The porosity is one of the most important parameters in oil & gas exploration as the hydrocarbons are situated inside the pore space.

Several geophysical methods were developed to estimate porosity. Two methods determine porosity by measuring the proxy parameter hydrogen contents, assuming the pore space filling to be water, which is valid in many sedimentary formations. In other rocks, e.g., metamorphic and igneous rocks, hydrogen is also abundant as bound water in the mineral crystals yielding too high porosity values. Pore space that is not water-filled cannot be detected by these methods.

The classic neutron porosity sonde measures the hydrogen contents in the formation which then can be translated into porosity if the matrix mineralogy is known. A neutron source (chemical or accelerator) emits neutrons into the formation. These most predominantly interact with hydrogen nuclei, which, when de-exciting emit gamma rays that are counted by the sonde.

The modern nuclear magnetic resonance sonde estimates porosity by measuring the decay signal of the spins of hydrogen nuclei excited by an ultra-strong magnetic field generated by the sonde. Note that the NMR sonde contains no radioactive source, other than the name might suggest. This sonde determines porosity independent from the matrix mineralogy. It can determine the pore size distribution and derive the permeability. The traditional porosity tools can only determine a total porosity, whereas the NMR is able to divide the porosity into different pore sizes (large pores for free fluids, pore in which the fluids are capillary-bound or irreducible, and clay-bound fluid).

Additionally, for comparison or if the nuclear sonde is unavailable (e.g., due to restrictions for nuclear sources) and also the NMR sonde is too expensive or has a too wide diameter for a slim hole, the sonic sonde can be used for porosity determination. Fluids inside the pore space generally have a lower velocity than the matrix. The recorded velocity represents the sum of the matrix and fluid velocities. Sonic waves are slowed down traveling through the pore fluids yielding a lower measured velocity than the matrix velocity: a low velocity indicates high porosity. If the velocities of the rock matrix and of borehole fluids are known (e.g., from core), porosity can be computed by using an empirical equation (for sandstones):

$$1/v_{p\text{-measured}} = (1-\phi)/v_{p\text{-matrix}} + \phi/v_{p\text{-fluid}}$$

The matrix velocity may be measured in non-porous zones of the same rock and the fluid velocity may be assumed to be that of the borehole fluid (measured).

**Magnetic Susceptibility**

The magnetic susceptibility (MSUS) is the ability of a material to be magnetized (Fig. 4.6.5). It is a unit-less parameter and should be given in the SI values (International System of Units), typically in $10^{-4}$. Be aware that old references probably give the magnetic susceptibility in values of the outdated cgs system, with 1 SI = 4π cgs. Rocks usually are paramagnetic with values spanning several decades between $10^{-6}$ and $10^{-2}$ in the SI system but of course also negative values (diamagnetic) may occur (e.g., water, graphite). The sonde imposes a magnetic field to the formation and measures the re-induced magnetic field.

The MSUS reflects the amount of magnetizable minerals in the formation, in particular titanomagnetites, pyrrhotites, and ores with high magnetic susceptibility. This log can determine stratigraphic changes in mineralogy and lithology (Fig. 4.6.5). It helps to localize boundaries of overlying lava flows and to identify zonation within a lava flow. In paleoclimate investigations of lake sediments, it is used as proxy for depositional conditions. In lake sediment drilling projects, it is the most powerful parameter for both the core-log depth correlation and to fill in data at core gaps to provide a continuous profile. MSUS can be used as a first-order indicator of climate-driven changes in sediment composition with high MSUS values indicating coarser sediments poor in carbonates and organic matter deposited during glacials/stadials and low MSUS values indicating finer sediments enriched in carbonates and organic matter deposited during interglacials/ interstadials.

**Dipmeter**

The dipmeter sonde basically is an oriented 4-arm caliper sonde with, additionally, an electrode bearing pad mounted to the end of each caliper arm. It furthermore provides the spatial orientation (dip and dip azimuth) of planar structures intersecting the borehole, like bedding planes, lamination, folding, faulting, fractures etc.. These structures are detected by the electrodes as resistivity contrasts on the borehole wall. With only 4 resistivity traces along the borehole circumference, the accuracy of the spatial orientation remains rather coarse.

**Borehole Imager**

Three types of borehole wall imager sondes deliver complementary information: acoustic, electrical, and optical. The first two require a borehole liquid (e.g., drilling mud, water), the optical one requires for clear, transparent borehole fluid, including gas (air). All three imager types are oriented by magnetometers and accelerometers (gravitationally).

The acoustic imager (also called borehole televiewer) emits an ultrasonic pulse to the borehole wall and measures both amplitude and travel time of the reflected signal. Either the sonic transducer or an acoustic mirror rotates around the sonde axis and hence takes many measurements per revolution (typically between 70 and 300 pulses/rev). The amplitude of the reflected signal depends strongly on the acoustic impedance of the borehole wall yielding an acoustic impedance contrast image of the wall (Fig. 4.6.5). The travel time measurement depicts variations of the borehole diameter, i.e., the caliper. This acoustic caliper image is like a multi-arm caliper log with very fine resolution. The travel-time-derived caliper relies on the knowledge of the actual fluid velocity, which varies with pressure and temperature. If possible, it is highly recommendable to estimate the fluid velocity inside hole sections with known diameters, e.g., inside casings or liners.

The best achievable image resolution (pixel size) is approximately $3 \times 3\ mm^2$ in a 76 mm hole and it decreases with increasing hole size.

The electric imager is an advanced dipmeter sonde with many more (> 50) and smaller electrode buttons on bigger pads. The small electrodes yield a pixel size of $5 \times 5\ mm^2$ independent of the hole size. This imager creates an image of resistivity contrasts (micro resistivity image). The electric images cannot completely cover the circumference in holes wider than as there is no data from the area between the pads, therefore blank stripes. Currently there is no real slim version of an electrical imager available for HQ bit size or even smaller.

In the optical imager a millimeter thin slice on the borehole wall is scanned by an optical camera, illuminated by LEDs. The resolution is $1 \times 1\ mm^2$ at best. This imager only works in air-filled holes or clear fluids (water). Any opaque fluid (typical mud) prohibits its use. The optical image is the best to compare with core pieces.

All three imagers yield oriented high-resolution images of the borehole wall. Features visible in one of the three imager types are not necessarily visible in the others because of their different physical properties.

The analysis of the borehole wall images allows to identify and orient structural dip, sedimentary dip, bedding, lamination, layering, thin beds, conglomeratic formations, lava flow boundaries and internal structuring, natural and induced fractures as well as stress induced BOs. Moreover, it easily allows to orient wireline-taken side wall cores. The set of oriented structures derived from imager logs and those derived from cores or core images can be used to orient these cores. Acoustic imagers are also used to inspect casings for corrosion and leakages.

**Temperature and Resistivity**

Logs of temperature and resistivity reflect the temporary, transient status of the fluid column inside the borehole. A temperature profile always is a superposition of the original, undisturbed temperature profile before drilling and the many effects of the hydraulic disturbance history of the well, mainly the mud circulation and other drilling procedures but also hydraulic tests. Usually the mud circulation cools a borehole down in the lower half and heats it up in the upper half. As a rule of thumb, the time it takes for the temperature profile to recover from the disturbances is the same as the duration of the disturbances. As this basically is the time period of the active drilling it would usually require many weeks or months of waiting (Fig. 4.6.6).

The Horner Plot method allows to estimate the original formation temperature with data from several stationary measurements repeated over several hours, or better a few days, at a certain depth, commonly bottom depth. Stationary temperature recordings over 10 to 15 minutes at the certain depth are repeated several times (≥ 4) distributed over many hours or a few days (the longer, the better). The highest T-value at the end of each recording is noted and the time of measurement $\Delta t$, where $\Delta t$ is the time since the thermal disturbance stopped. The measured temperature values are plotted on a linear y-axis vs. a logarithmic x-axis of

$$(\Delta t + tc)/\Delta t$$

where *tc* is the duration of the disturbance (in practice this is the time of drilling the last several meters plus all circulation time). In this semi-logarithmic plot, all points will define a best-fit straight line. The intersection of the best-fit line with the temperature axis at the value 1 on the x-axis approximates the undisturbed formation temperature.

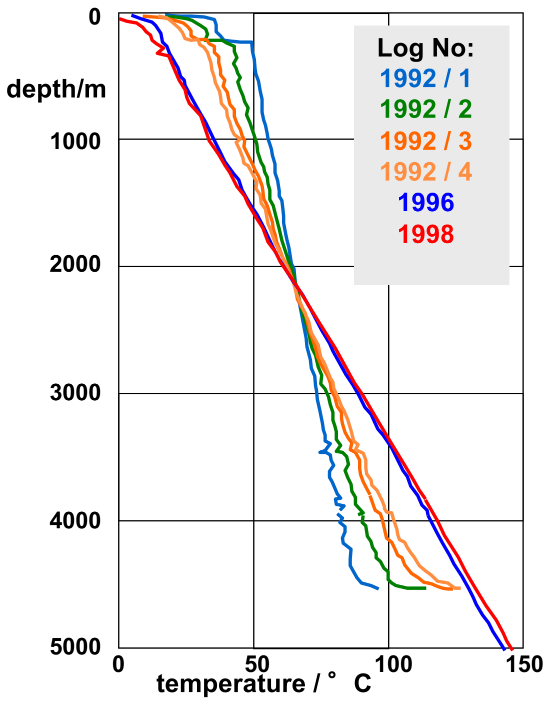


*Fig. 4.6.6: An example of temperature equilibration in a deep borehole. The curves from 1992 were measured after the hole was drilled to 4500 m.*

A fluid resistivity profile even more captures the very transient distribution of multitude mixing fluids of varying resistivity. Therefore, the profiles of both temperature and resistivity indicate zones or spots (open fractures) of active fluid flow into or out of the formation. Such flow may be driven by differences of salinity, temperature, and pressure of the formation fluids compared to the drilling fluid. Resistivity logs can be used to suggest a lithology as certain minerals have distinctive although not exclusive values. Generally, high resistivity may be diagnostic of salt, anhydrite, gypsum and coal, and also associated with tight limestones and dolomites. On the contrary, low resistivity is generally not diagnostic, although shale has usually low values.

**Core-log-seismic integration**

Downhole logging data can be used to augment core-derived data and to fill the frequently unavoidable gaps in the core record. Core-log integration is very often understood as core-log depth correlation, although this is only a very small aspect of it.

**Core-log depth matching**

Comparison of parameters from the discontinuous core sequence with the continuous profiles of logging parameters enables to correct the core depth according to the logging depth (depth matching). In principle any parameter can be used for this but in practice the total natural gamma radiation (GR) and/or the magnetic susceptibility (MSUS) are used by far most often. The reason is that a downhole GR log is run in almost every project. The measurement of GR on the core is not as easy as of other parameters and hence not available in every project. The MSUS is an even better depth correlation parameter for being very easy to measure on the core, having a very high repeatability without statistical variations of the GR and the same good vertical resolution as the GR of less than 20 cm. Of course, not all formations feature articulated variations of the MS or GR profile, which are necessary for a good depth correlation quality. Uniform, not sharply varying curves do not reliably allow a depth correlation. The traditional depth matching is done by a visual correlation of peak patterns or peak-to-peak.

**Orienting drill cores with images**

For any structural investigation, the accurate orientation of fractures, veins, faults, beddings in drill cores is crucial. Direct orientation of the core during the drilling is not a standard procedure. In the absence of a direct orientation, an indirect method can be used, where features on the core are correlated to those in oriented borehole images. Planar elements such as fractures, beddings, joints, etc., intersecting a cylinder, here the core and the borehole, appear as sinusoidal lines in the unrolled cylinder surfaces, here the core scan and the borehole image (Fig. 4.6.7).

First, the whole cores (not half-cores!) will be scanned in high resolution yielding core scans that have an apparent orientation, preliminary to a reference mark (see chapter 4.6 for details). To north-orient the cores, the core scans are imported into a dedicated software (e.g., WellCAD) as unrolled 360° images for direct side by side comparison.

Warning: the azimuth scale of either the scan or the borehole image has to be reversed, usually this is done to the core data. This is necessary because of the different viewing directions of core scanner and borehole imager. The scanner looks from the outside onto the core, the imager looks from inside the hole to the borehole wall.

If the core depth has not already been matched to the logging depth (GR or MSUS matching), matching of the planar features can be used to correct for the depth shift between each individual core scan and the borehole image as master reference. This matching is critical in the orientation process because larger depth discrepancies between core depths and borehole image logs can lead to incorrect feature correlation. After that, the preliminary azimuth of the core scan is shifted iteratively, which corresponds to a rotation of the real core, until the set of sine curves matches the set displayed in the borehole image. When all core scans are oriented this way, the structural analysis (dip and dip direction) on core can start.

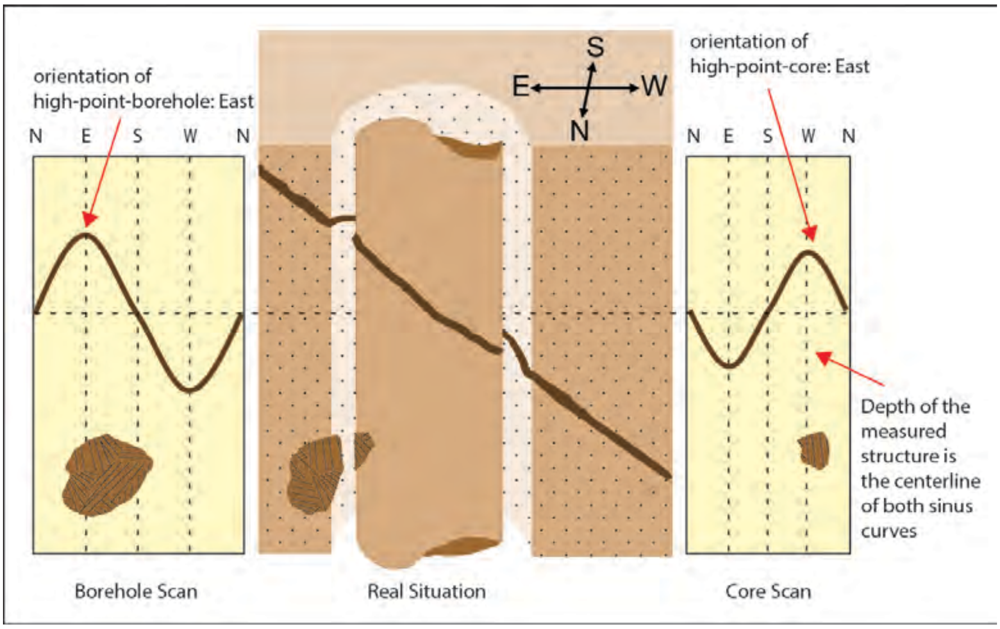


*Fig. 4.6.7: Comparison of structural features in borehole wall images (left) and core images (right)*

**Core-log seismic data integration**

The combination of core, log and seismic measurements contributes to the confidence of each data set, reduces the key uncertainties associated with formation evaluation, obtains high-resolution seismic stratigraphy and improves the knowledge on physical properties of the rocks. This method bridges lab data on samples with in situ logging information and spans scales from the sub millimetre-scale of core investigations to the decimetre scale of logging data and ultimately the metre scale of seismic data. This multi-scale approach is well-known as core-log-seismic integration - CLSI (Fig. 4.6.8).

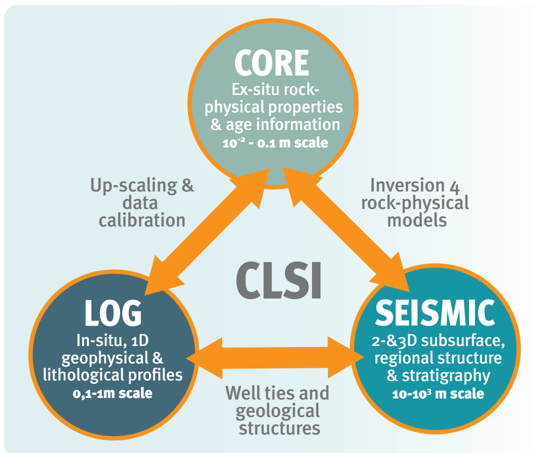


*Fig. 4.6.8: The CLSI method integrates and connects several investigation methods at different scales*

Two major steps are necessary before applying the CLSI method: core-log and log-seismic integration. The first step has been described above. The second step matches logging data with seismic data. Synthetic seismograms are produced from the density and p-wave velocity logs. Additionally, this synthetic seismogram can be related to the corridor stack that is calculated from zero-offset VSP (vertical seismic profiling) data and with the 2D and 3D data of the seismic sections near the borehole. After individual integration (core-log and log-seismic) a joint integration based on the synthetic seismogram can be pursued. Detailed CLSI enables us to infer lateral variations of physical properties along the seismic reflection profile and to interpret the seismic data in terms of the measured formation properties. It is essential to expand these physical properties into 2-D and/or 3-D to better characterize the continuous and high-amplitude reflectors on seismic profiles.

**Electrofacies analysis**

The electrofacies analysis is a powerful logging data evaluation method to derive a very detailed lithological profile (electrofacies log) and supports core-log integration. This analysis differentiates borehole sections based only on their set of characteristic values of various logging parameters. As described in the introduction the log response of a sonde results from the physical properties of the formation surrounding the sonde sensors, where formation = rock + in-situ conditions. In other words, each identified section is univocally characterized by the combination of typical value ranges of several parameters. For the analysis it is initially irrelevant which material actually is existent in the sections. Identification with geological units happens at the end of the analysis.

A multi-dimensional cluster analysis using all independent log parameters identifies groups or classes with the same set of value ranges. These groups are called electrofacies. The quality of the electrofacies log usually increases with the number of available independent logging parameters, i.e., the more log parameters are available, the more formation types can be differentiated and the more distinctively.

To identify the corresponding geological, structural, or geomechanical units the electrofacies have to be calibrated by comparison with core data. This yields a translation protocol from electrofacies to geological units. The electrofacies analysis can yield a higher vertical resolution and even more units than derived from the core. This requires revisiting the core data for a more detailed inspection at the depths of the non-identified electrofacies. The translation protocol can then be used on the electrofacies log in hole sections without core gain, filling these gaps of core data. In addition, it can be applied to electrofacies logs from adjacent non-core wells in the same geological setting, eliminating the need for expensive core drilling there. The method can furthermore help to identify fracture zones.

**Fluid flow and fracture systems**

A wide variety of downhole logs aids to identify, localize, and characterize open fracture systems and the linked flow and fluid regimes. The primary parameters to indicate and characterize flow zones are fluid temperature, fluid resistivity (MRES), and fluid flow as they depict the current state of fluid movement in the borehole. These measurements are best run in combination with controlled hydraulic tests, e.g., draw-down or pumping tests, because these tests usually stimulate a higher influx. Repeated runs at constant hydraulic conditions of a lowered fluid level (draw-down or pumping test) may even allow the quantification of the individual flow zones and of cross-flow within the borehole. The flow rate profile along the hole can be measured directly with flowmeter sondes. Subsequent downhole fluid sampling with special sondes can be positioned with a very high depth accuracy.

Warning: Lowering the fluid level in a borehole bears the potential risk of destabilizing the borehole wall, which can lead to hole collapse and in the worst case to the loss of downhole tools or even the hole itself.

Already during a regular logging session, i.e., without any hydraulic stimulation, some logs can indicate open fractures and fracture zones, e.g., sonic, formation resistivity, borehole images, uranium from SGR, and caliper. Fractured zones in an elsewhere intact formation can appear as anomalies in sonic and resistivity logs. The scattering fractures dissipate the sonic wave energy causing so-called chevron patterns in sonic waveforms. If the Stoneley velocity can be determined from the waveforms it can be used to detect open fractures due to their pronounced attenuation and reflection in fractured zones.

Already the measured deep and shallow formation resistivity (radius of investigation) can show zones of fluid filled, i.e., open fractures, with values significantly higher or lower than the intact formation around the fracs. Enhanced sensitivity provides a curve calculated curve of the difference *deep minus shallow* formation resistivity.

Fractured zones may appear as zones of borehole enlargements in a caliper log. The highly mobile uranium may have accumulated in the fractures yielding uranium peaks.

Borehole images, both acoustic and electric, will show open fractures with a very high depth resolution. Moreover, the acoustic imager can differ open from healed/closed fractures as open fracs should be visible on the travel time image, closed fracs not.

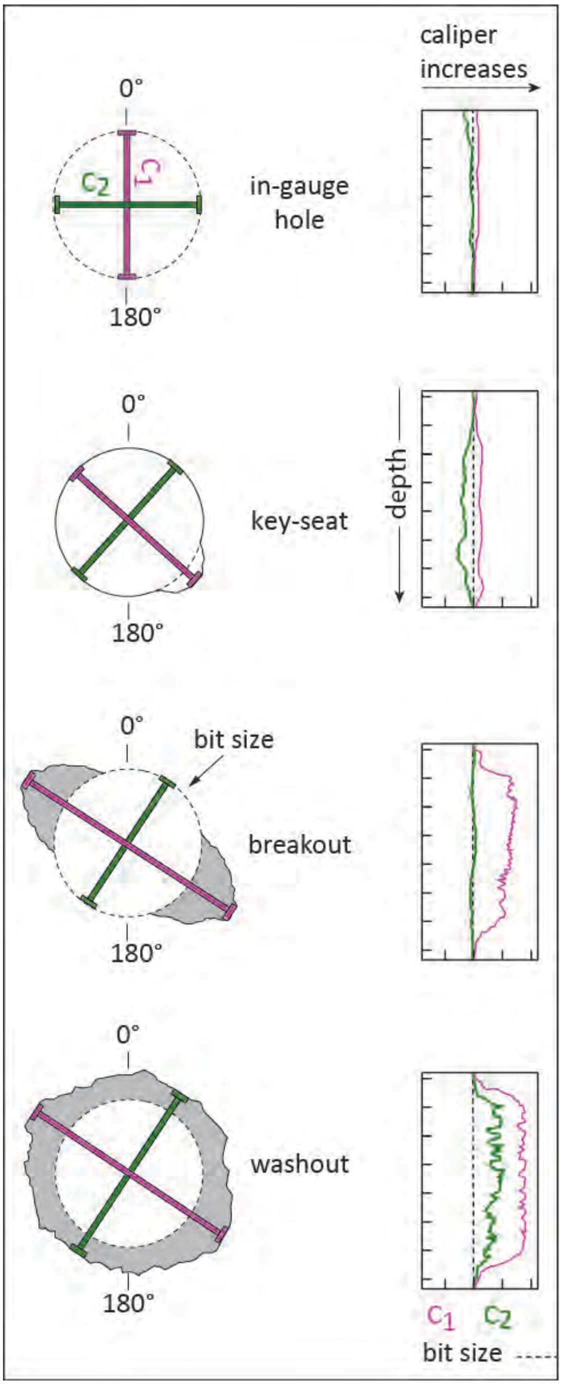


Fig. 4.6.9: *Sketch of borehole size and shape (left column) and the corresponding caliper curves (right).*

**Structural analysis and stress field**

The analysis of acoustic and electric borehole images and dipmeter data provides useful information regarding borehole size (breakout, washout, key-seat; Fig. 4.6.9), dips of bedding planes (to identify folding, faulting and unconformity features), the present-day stress field, sedimentological studies (turbidites, beds, bioturbation, concretions, clasts), and igneous features (veins, alteration, lava pillows, breccias, flows).

The analysis of acoustic borehole images allows to detect structural features, natural fractures, thin beds, bedding dip, to orient core samples, to inspect the casing conditions and to identify induced tensile fractures (DITFs) and borehole enlargements (e.g., washouts, breakouts). DIFTs and BOs are important features to determine the present-day stress field orientation.

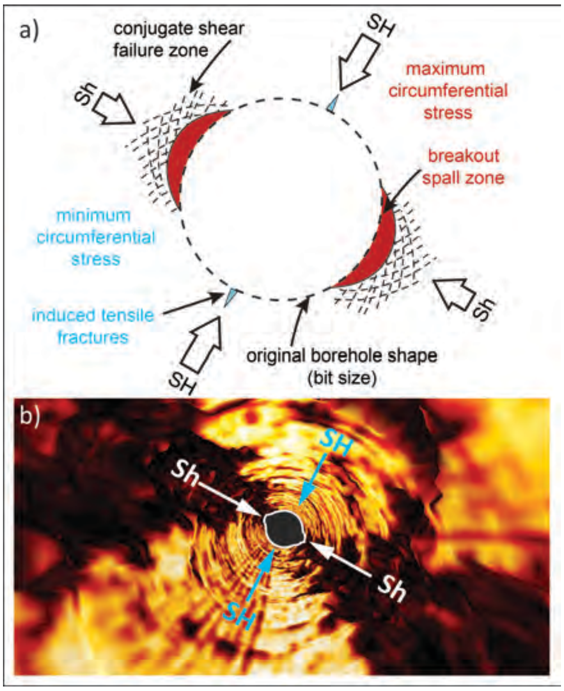


*Fig. 4.6.10: Borehole breakout shape. a) In vertical holes breakout zones develop at diametrically opposing sides with the long axis of the elliptical zone parallel to the orientation of the minimum horizontal principal stress (Sh). Perpendicular to the long axis, induced tensile fractures can appear and their orientation is parallel to the maximum horizontal principal stress (SH). b) 3-D borehole breakout view from ABI image of the borehole wall.*

When drilling a borehole into the Earth's crust, which is under a non-uniform in situ stress condition, rock failure can occur around the borehole where stress concentrations exceed the rock strength.

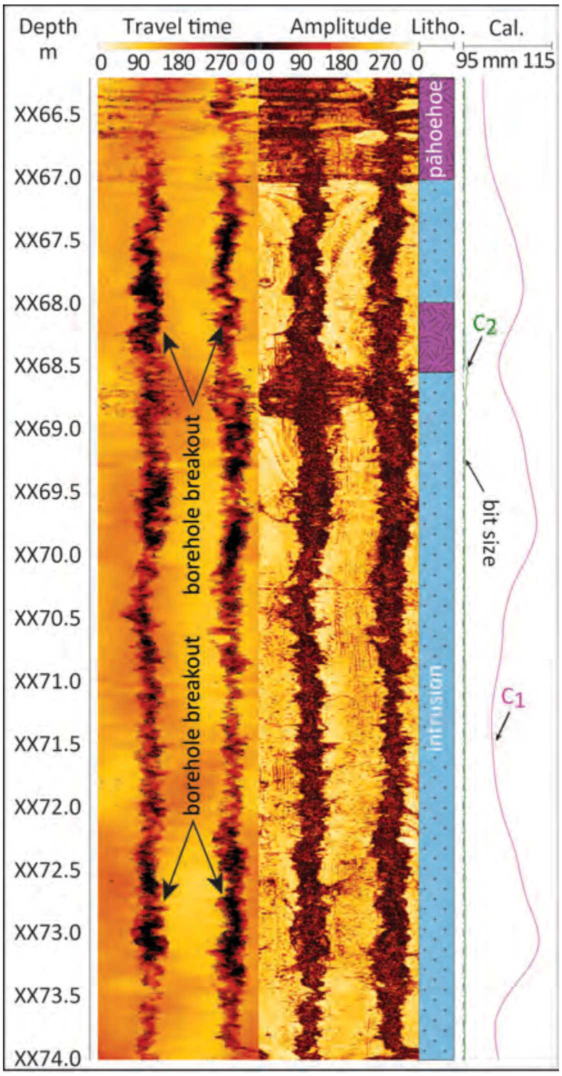


*Fig. 4.6.11: Borehole breakouts appear as pair of dark, patchy stripes on opposing sides of the wellbore wall characterized by low amplitude and high travel time values.*

Breakout enlargements occur where the compressive stress is maximum around the borehole circumference. Here intersecting conjugate shear planes can form, causing pieces of the borehole wall to spall off. The enlarged area is called borehole breakout (BO), which elongates in a preferential orientation parallel to the minimum horizontal principal stress axis, Sh (Fig. 4.6.10).

The BOs are not the only type of the stress induced damage seen on the borehole wall. Also, drilling-induced tensile fractures may be detected on borehole images that are useful for determination of the current stress field orientation. The DITFs occur where the tensile stress concentration is maximum at the borehole circumference. Hence, these features develop parallel to the maximum horizontal principal stress axis (SH). BOs and DITFs occur only on the borehole wall, not on cores.

Acoustic borehole images are commonly scaled and color-coded in a way that borehole enlargements appear as dark features (high travel time & low amplitude). BOs therefore appear as two dark, patchy stripes on opposite sides of the hole (Fig. 4.6.11). Also, electrical images will show these features but not so pronounced and only fragmentary as the borehole circumference is not covered entirely. Sometimes, where the spalling off the borehole wall has not yet developed, incipient BOs are only one or a narrow swarm of sub-vertical fractures at Sh directions. These may be identified on acoustic and electrical images as several parallel sub-vertical, dark lines. DITFs also appear as dark lines both in acoustic and electrical images. They are mainly sub-parallel to the axis of the borehole and their trace is not as continuous as the BOs are.

On the contrary, natural fractures commonly appear as quasi-continuous sine curves of lower or higher resistivity (electrical image) or of different amplitude (acoustic) than the surrounding rock (Fig. 4.6.12). A consistent population of natural fractures can be used to reconstruct the paleo-stress field. These data are compared with existing stress records of the area to obtain an improved knowledge of present-day stress field in the area. A detailed understanding of the regional field is a fundamental contribution in several research areas such as geothermal reservoir studies, or exploration and exploitation of underground resources.

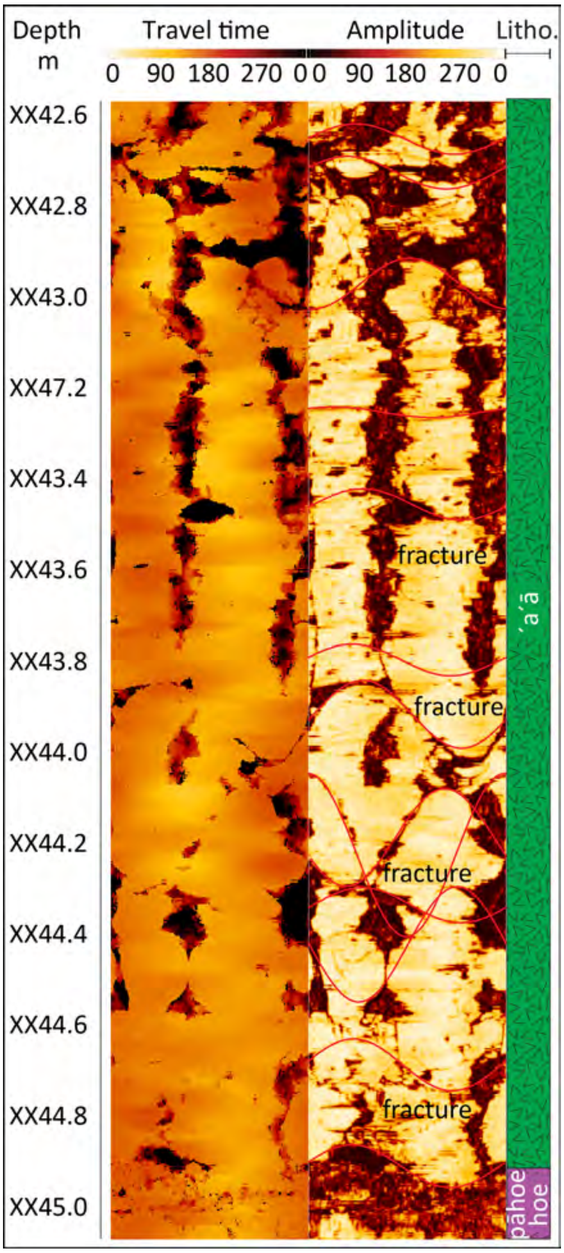

*Fig. 4.6.12: Fractures on an acoustic image log*

**Orientation and magnitude of stress**

Knowledge of orientation and magnitudes of the present-day stress field at depth is relevant both for the geologic sciences and engineering applications. The orientation is determined by BO analysis (Acoustic Imager and Dipmeter) explained in the section *'Borehole size and tectonic features',* whereas the magnitude of principal vertical stress (Sv) is calculated from density measurements; the magnitude of the least horizontal principal stress (S3, which is usually Sh) is mainly determined from well testing (hydraulic fracturing data, leak-off tests), and the maximum horizontal principal stress (SH) is generally calculated by empirical formulas. The magnitude of the three principal stresses is a good indicator to determine the kind of stress regime (normal faulting Sv>SH>Sh; strike-slip faulting SH>Sv>Sh; thrust faulting SH>Sh>Sv). Stress orientation and relative magnitudes are used to define the first, second and third-order stress patterns acting in the study area.

**Lithology and mineralogy identification**
The potassium content of various clay minerals varies considerably, for example illites (which are micas) contain a large amount of potassium. On the contrary smectite and kaolinite (both clay minerals) have little or absent content of potassium. Potassium is present in K-feldspar in microcline and orthoclase minerals. Carbonates usually display a low gamma ray signature. An increase of potassium can be related to an algal origin, or to the presence of glauconite. Thorium is abundant in acid and intermediate igneous rocks and frequently found in ash layers, in bauxite, in shales, and in heavy minerals, such as epidote, thorite, zircon, sphene and monazite. Thorium is also concentrating in sediments of terrestrial and marine origin such as kaolinite and glauconite, respectively. Uranium is found particularly in acid igneous rocks, black shales (stagnant, anoxic water with slow rate of sedimentation), phosphatic rocks and is often associated with organic matter. The Th/K ratio can be applied to the recognition of clay minerals and distinction of micas and K-feldspars because the ratio is a relative measure of K abundance relative to Th. The Th/U ratio has also proven to be useful as indicator of redox conditions, and it can also help to detect ash layers.

## OSG DOWNHOLE LOGGING EQUIPMENT

Based on the most frequent requirements of ICDP projects OSG established ICDP downhole logging equipment with slimhole probes and suitable logging winches. The tool specifications allow utilization in very different hole conditions. The lightweight equipment allows low-cost shipment to remote locations and at difficult conditions (Figures 4.6.13 and 4.6.14). The acquired logging data are quality checked and depth corrected by OSG. MSUS, GR and SGR data are corrected for sonde centering/ eccentering, hole size, mud type, and casing attenuation with respect to the reference of logging inside an 8-inch borehole filled with fresh water.

*Fig. 4.6.13: Logging winch with 2.2 km of a 4-conductor cable.*

The data output formats are the universally used and transferrable formats DLIS, ASCII and WellCAD.

**OSG wireline sondes**
The OSG wireline slimhole sonde set covers

basic geophysical logging parameters:

- electrical resistivity (electrode & induction)
- sonic velocity
- natural gamma ray spectrum
- total natural gamma ray
- 4-arm caliper, borehole orientation, structural data (4-arm dipmeter)
- magnetic field, total & vertical
- magnetic susceptibility
- spontaneous potential
- acoustic borehole wall images (aka televiewer)
- mud parameters (temperature, pressure, resistivity)
- fluid samples
- seismics (3-component borehole geophone chain, 17 levels)

Further information is listed in Table 4.6.3.

*Fig. 4.6.14: Small and lightweight OSG downhole logging equipment ready to be shipped.*

OSG does not operate tools with nuclear sources, hence there are no density and neutron porosity sondes. All tools are rated for a minimum of 150°C and 50 MPa, except for the televiewer (125°C/50 MPa) and can be used in hole sizes as small as 75 mm (Figure 4.6.15). The maximum borehole size differs for each tool. Details are listed in Table 4.3 below.

These tools are best run on our special slimhole logging winches but also work on any logging winch system with at least a 4-conductor logging cable and GO4 or GO7 cable head.

*Fig. 4.6.15: OSG slimhole wireline logging sondes at a drill site*

**OSG memory logging system**

Since 2020 OSG operates a new memory logging sondes system (iMLS). The system comprises the battery powered and autonomously measuring downhole logging sondes (SGR, MSUS, TEMP, sonic and induction resistivity) and a surface-based depth measuring device (Figure 4.6.16); details are provided in Table 4.6.4. For a logging run a memory sonde combination with a special landing tool mounted on top is thrown into the drill pipe where it sinks down and ultimately lands at the drill bit. Some sondes of the sonde string stay inside the drill pipe others protrude through the bit into the open hole. During trip-out of the rill string the memory sondes are pulled up towards surface while they are recording. Via correlation of the downhole recorded time and the time recorded simultaneously in the depth measuring device at surface, the depth trace is merged with the downhole data. With use of an appendant telemetry sonde the OSG memory tools can also be run in online mode like regular wireline sondes. The memory sondes are rated 70°C/50 MPa.

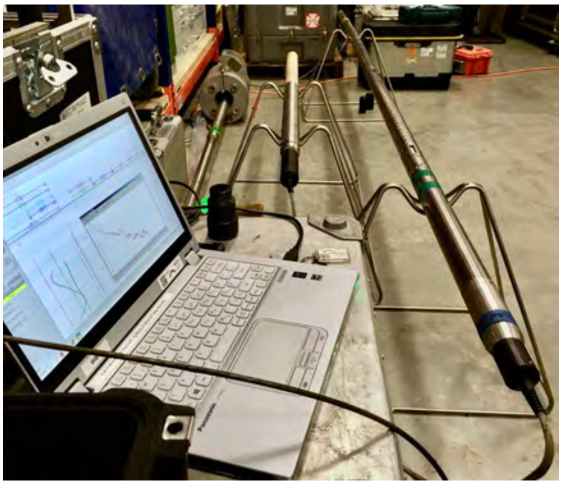

*Fig. 4.6.16: OSG slimhole memory logging sondes during a workshop test*

*Table 4.6.3: OSG wireline logging tools as of 2020.*

## OSG Slimhole Wireline Logging Sondes

J.Kück 2020-SEP

| **Tool Type** | **Sonde Name**<br>**Parameter** | **T/p/Ø/length/weight/min.OH Ø/**<br>**max. hole Ø /log speed** |
|---|---|---|
| Telemetry | **TS**<br>telemetry, total natural Gamma Ray, motion detector, CCL | 150°C/50 MPa/43 mm/1.29 m/7 kg/<br>≈75 mm/-/10-20 m/min |
| Electric | **DLL**<br>dual laterolog resistivities: deep & shallow (bottom tool) | 150°C/80 MPa/43 mm/2.2 m w/o bridle/ 13 kg/ length bridle cable: 6.0 m<br>≈75 mm/250 mm/12-20 m/min |
| | **SP**<br>spontaneous potential (analog sonde, standalone) | 150°C/30 MPa/43 mm/0.86 m/3 kg/<br>≈60 mm/250 mm/12 m/min |
| Sonic | **BS**<br>borehole sonic, full waveforms (with centralizers) | 150°C/80 MPa/52 mm/≈4.5 m/23 kg/<br>≈75 mm/ 250 mm/6-8 m/min |
| Gamma | **SGR** & **GR**<br>spectrum of natural Gamma Ray activity:<br>U, Th, K & total natural GR (combinable) | 150°C/80 MPa/52 mm/1.24 m/11 kg/<br>≈75 mm/250 mm/< 3 m/min (9m/min only GR) |
| Magnetic | **MS**<br>magnetic susceptibility (bottom tool) | 150°C/80 MPa/43 mm/1.9 m/9 kg/<br>≈75 mm/500 mm/8-12 m/min |
| | **DIP** slim<br>total & vertical magn. field amplitude (bottom tool) | see under the following item |
| Geometry | **DIP**<br>oriented 4-arm dipmeter, four independent caliper readings, borehole geometry (bottom sonde) | 150°C/80 MPa/52 mm/2.69 m/13 kg/<br>≈75 mm/250 mm/9 m/min |
| Images | **ABI43** incl. **GR**<br>acoustic televiewer, total natural GR<br>(with centralizers, standalone sonde system, ALT) | 125°C/70 MPa/43 mm/3 m/14 kg/<br>≈60 mm/500 mm/2-5 m/min |
| Mud Parameters | **MP**<br>mud temperature, pressure & resistivity (combinable) | 150°C/80 MPa/43 mm/0.8+2.0 m/14 kg/<br>≈75 mm/-/5-15 m/min |
| | **TEMP**<br>mud temperature (bottom tool) | 150°C/80 MPa/43 mm/1.05 m/8 kg/<br>≈75 mm/-/5-15 m/min |
| Seismics | **SGC *SlimWave*** incl. **GR** & **CCL**<br>borehole geophone chain, 3-comp, 15 Hz, 17 levels (standalone sonde system, Sercel) | 135 °C (150 °C)/100 MPa/43 mm/1.1 m/ 6.5 kg/≈75 mm/178 mm/stationary, level spacing: 10m, max. weight 260 kg |
| Fluid Sampler | **PDS (FS)**<br>600 $cm^3$, positive displacement type, mercury-free (combinable w/ TS-MP) Leutert | 180°C/100MPa/43 mm/3.9 m/30 kg/<br>≈65 mm/-/stationary |

The telemetry sub must be combined with all other sondes, except for ABI43, SP, SGC and FS. It has a GO7 cable head connection. All slimhole tools are digital, except for SP and FS. The digital sondes require at least a single-conductor cable, except for DLL and ABI which require for a 4-conductor cable.
Possible tool combinations: SGR-MS, SGR-DLL, SGR-DIP, SGR-BS-MS, SGR-MP-MS, BS-MP-MS,SGR-MP-DIP.

*Table 4.6.4: OSG memory logging tools as of 2020.*

## OSG Slimhole Memory Logging Sondes

J.Kück 2020-SEP

| **Tool Type** | **Sonde Name**<br>Parameter | **T/p/Ø/length/weight/min.OH Ø/ max. hole Ø /log speed** |
|---|---|---|
| Memory-Battery | **MEMBAT**<br>memory, battery, acceleration | 70°C/50 MPa/43 mm/1.25 m/6.5 kg/<br>75 mm/-/- |
| Telemetry | **mTS**<br>telemetry sub for use of iMLS tools in wireline mode (= online) | 70°C/50 MPa/43 mm/1.29 m/8 kg/<br>75 mm/-/- |
| Gamma | **mSGR**<br>spectrum of natural Gamma Ray activity:<br>U, Th, K & total natural GR, inclination (combinable) | 70°C/50 MPa/52 mm/1.24 m/11 kg/<br>≈75 mm/250 mm/3 m/min |
| Magnetic | **mMS**<br>magnetic susceptibility, temperature (bottom tool) | 70°C/50 MPa/52 mm/1.4 m/7.5 kg/<br>≈75 mm/250 mm/6 m/min |
| Electric | **mDIL**<br>dual induction resistivities: deep & shallow; hole deviation (bottom tool) | 70°C/50 MPa/43 mm/1.9 m/10 kg/<br>75 mm/250 mm/6 m/min |
| Sonic | **mBCS**<br>borehole compensated sonic, full waveforms<br>(tool with centralizers; combinable) | 70°C/50 MPa/52 mm/≈ 3.9 m/27 kg/<br>75 mm/250 mm/6 m/min |

These sondes can be run either in memory mode, with memory-battery sub (MEMBAT) or in wireline/online mode with telemetry sub (mTS) on top. The mTS has a GO4 cable head connection. The MEMBAT sub can be equipped with a mechanical GO4 head connection or with a fishing neck (spear head) to be deployed as *logging while tripping* of the drill string. The iMLS can also be deployed on a rope from any winch with a depth measuring system. Either MEMBAT or mTS combined with the mSGR are required to run all other memory tools. All memory tools are digital. In wireline mode they require at least a 4-conductor cable.
Possible tool strings: SGR-MSUS, SGR-DIL, SGR-BCS, SGR-BCS-MSUS, SGR-BCS-DIL.

Updates on logging support and logging equipment of the OSG are provided on the ICDP web pages at: *www.icdp-online.org/support/service/downhole-logging/operational-support/* and *www.icdp-online.org/support/equipment/downhole-logging*

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CHAPTER 4.7

# Geophysical and Geochemical Borehole Monitoring

**Bernhard Prevedel*, Martin Zimmer# and Jan Henninges§**

This chapter summarizes the current state of the art in Permanent Downhole Monitoring (PDM), continuous fluid sampling and it provides an outlook and recommendation for future development and research needs. It also proposes suggestions and decision aids for Principal Investigators and scientists in reference to their selection criteria for a specific measurement sensor or PDM installation. The PDM systems available today in industry and academia represent a final wellbore installation, similar to a borehole completion in oil or geothermal wells, but in this case not for energy but data production to surface. They are generally categorized in two types of installations:

- Type 1: Outside the casing, facing the rock formation and permanently cemented in place
- Type 2: Inside a cased or open hole by means of wire-line or pipe deployment with an option to be retrieved to surface for repair or inspection

Common to both types is the requirement for a long downhole life expectancy in the form of system reliability of a minimum of 5 years mean time between failures (MTBF) combined with safe measurement repeatability over comparable periods. In the array design criteria special emphasis has to be given to redundancy of sensors and telemetry lines in order to mitigate the risk for premature or a system failure. In an attempt to cover the majority of the potential scientific PDM applications a minimum environmental regime of 125 °C at 500 bar for +20.000 hours continuous operation should be targeted for the component selection. High temperature and deep installations will require a much more constrained specification envelope, and the cost of PDM hardware and installation will increase. Every PDM system will consists as a minimum of a deployment system, hole-anchoring system, sensors and data recording and data management units.


*Fig. 4.7.1: GFZ logging winch with 7000 m 7-veneer cable deployed in Otaniemi, Finland*

**Deployment system**

A deployment or conveyance system is the means to transport the instrumentation in and out of the hole, which serves at the same time as the instrument's umbilical to the surface. Fundamental basis for a PDM system is therefore a reliable deployment mechanism for a safe installation downhole. The most common and versatile way to deploy borehole instrumentation in a borehole is by means of a wireline (Fig. 4.7.1). The value of a wireline operation lies in its independency from any rig or special surface installation. It typically requires only a tripod over the wellhead or sometimes a crane if long tool strings have to be handled.

Wire ropes and slick line cables are the simplest well servicing tools and come in the form of truck-mounted winches with several 1000 m rope length to small hand portable winches with a few hundred meters. But they do not have any electric conductor and were used in the past primarily for the installation of mechanical measurement devices or memory gages. Complex surface powered or fiber-optic sensors systems can also be deployed by clamping their non-armored PU data cables (Polyurethane) to a tubing string or rope line. Rigid clamping needs to occur in discrete intervals minimum every 15 m in order to sufficiently support the weight of the PU cables and avoid slippage along the carrier and prevent cable tear.

Only a few standardized procedures or commercial clamp designs are available on the market, and designs in the past were often customized solutions. Some installations worked perfect for years of downhole operation (i.e., Long Valley, USA) and some failed before even reaching the depth of installation. Careful planning and calculation of instrument weight and buoyancy as well as cable tension, frequent selection of clamping intervals and enough room for installation time is a good basis for achieving best results.

Armored electric cables were originally developed for electric wireline logging under very harsh conditions in oil & gas drilling. The design typically consists of two components, the mechanical outer armor and the electrical core. The armor is comprised of two layers of counter-helically twisted steel wires. Inside is a core of individually insulated conductors (copper lines) wrapped in a plastic coating (Fig. 4.7.2).

The required outer diameter (typically: 7/16” or 3/16”) depended on the desired breaking strength of the logging cable and the number of electrical conductors needed. There are cables available with 7, 4, 3, or only one electric conductor and with or without fiber-optical leads. Usually the outer armor is used for the electric return. It is made of galvanized high-strength steel, rarely of stainless alloys or even titanium and may be plastic coated or silver-plated depending on borehole temperature and corrosive borehole conditions. For special sensors and very high data transmission armored electric cable can be augmented by a small metal tube containing typically 3-4 fiber-optic leads.

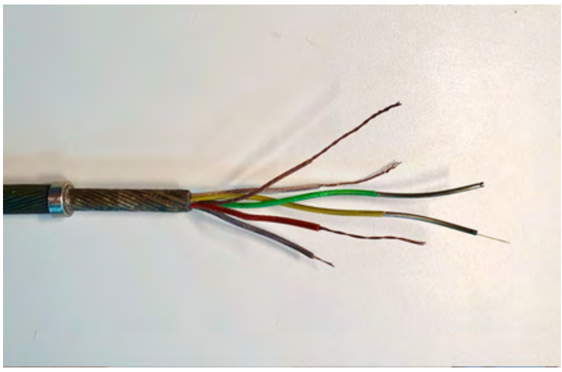

*Fig. 4.7.2: Armored wireline cable with 4 electric and 2 steel tubes holding optical leads*

The oil & gas industry promoted the development of a steel material to be employed as endless production tubing stored on a reel, called coiled tubing (CT). With that device operators were no longer in need of a rig to repair and work-over live production wells. This ability turned out to be extremely cost-effective in particular for offshore production fields, allowing the expensive rigs to concentrate on drilling projects.

Coiled tubing is made from a highly ductile steel alloy that recovers its initial strength even after being plastically deformed beyond yield. On the other hand, it is also a material that had a greatly reduced breaking stress capacity at very much reduced fatigue cycles compared to high graded steel. Therefore, the number of cycles (off/on reel motion) combined with the actual stress in the material from pull and internal/external pressure needs to be carefully monitored for each CT unit in the field to avoid premature failure in the hole. But a CT well intervention is also a heavy and expensive operation. On a land location it requires approximately the same footprint and access roads as for a mid-sized medium-to- heavy drill rig (Fig. 4.7.3).

*Fig. 4.7.3: Skid-mounted coiled tubing unit (Wikipedia, CC BY-SA 4.0)*

In horizontal and highly deviated wells (> 60 degrees from vertical) sensor packages cannot be deployed by gravity only on a standard wireline, but instead special techniques are necessary to position the sondes downhole. One option is to use the much stiffer coiled tubing with a conventional armored wireline cable installed inside to push the logging tools down in such high angle well sections. This procedure is also applied with CT Logging. However, in long high angle and horizontal open-hole sections even the CT also has at the same point the tendency to helically lock in the well bore, if the friction force exceeds downward thrust. The CT then behaves like a wire rope under loss of compressive strength. In such an event, the only further option is conveyance on drill pipe or production tubing.

In order to improve life and the number of safe bending cycles a material other than steel was looked for and found in Composite Coil Tubing (CCT) with embedded conductors or lines in the body of the composite structure. Composites are the logic answer; however, it took many years of research to arrive at a material technology that was able to sustain the typical downhole well temperatures of 150°C and higher. Today CCT sizes are available in the range from 1” to 24” with mechanical performances similar to steel pipe, but only half its weight and a multiple of bending cycle capacities. In addition, electric wires, FO strands and even hydraulic lines can be woven into the composite fabric, such becoming an integral part of the pipe body. The procedure of installing the monitoring instrumentation with a CCT is the same as with classic CT via an injector head and crane or truck-mounted derrick support.

Installation on drill pipe for permanent downhole monitoring is rarely done due to high costs and the required drill rig for such an operation. However, when the risk of getting stuck in the hole exists and extreme pull-free forces are expected, then this mode of conveyance has to be favored over all other options, despite of the high costs involved.

**Hole-anchoring system**

Hole-locks are positively activated devices that anchor repeatedly and firmly a monitoring device in a hole and assure no relative motion of the tool vis-à-vis the borehole wall over weeks or even years. Different types of measurements require a different quality of locking mechanism, which is generally described by its lock force to instrument weight ratio and duration of locking period. Typically, geo-mechanical measurements require the highest quality hole-locking, followed by seismic sensors. Geochemical and geo-electrical sensors are almost insensitive to hole positioning and some require no hole lock at all.

*Fig. 4.7.4: Spring bow de-centralizer hole lock concept (photo: SAFOD project)*

Mechanical, hydraulic and free-suspended settable locking devices on cable or pipe are mostly based on mechanical spring bow wireline logging centralizers and represent the simplest but also most versatile type of maintaining a reference to the borehole in space. The oldest but at the same time very efficient concepts is a spring supported steel bow design that created enough friction on the side of the hole that the tool would not move voluntarily except by pulling on the cable from surface (Fig. 4.7.4) Enhanced designs had electric actuators or stepper motors in the tool downhole that pumped up the bows or steel claw enforced lock arms and released them again on command (Fig. 4.7.5). Failsafe mechanical overrides, like shear pins or burst discs ensured that the tool could be recovered even when the release mechanism could not be reactivated for various reasons.

Hydraulic locking devices are almost entirely confined to CT or pipe conveyance, as hydraulic actuation lines can typically not be installed together with cables. Mechanically or hydraulically inflatable packers are reliable and efficient hole locking devices to anchor instruments firmly in the hole for very long monitoring periods. Releasing them even after years is almost uncritical due to the presence of pipes for applying the required pull-free force. In addition, these devices can be set and released multiple times with virtually any lock force that is acceptable by the borehole. If required, the anchoring can also be done in an oriented mode and even with mechanical decoupling of the anchored array from the conveyance pipe string above in order to avoid pick-up of noise frequencies from above hole sections.

However, from the logging experience at the German KTB boreholes and other deep PDM installations all over the world, the preferred way for an optimum sensor coupling to the rock formation today seem to be (1) downhole installations with permanent anchor systems or (2) permanently cemented and non-retrievable sensor arrays.

*Fig. 4.7.5: Three stages of DS 250 3c geophone package with activated hole locks (photo: SAFOD project)*

**Sensors**
The availability of measurement sensors in the industry and academia is actually quite large and they are basically divided into 2 families:

- active powered sensors
- passive operating sensors

As the definition indicates, active powered sensors do require external power in order to take a measurement. They usually also come with a digital output so that an array of these sensors can easily be combined into one single electric transmission line. By comparison, passive sensors are mechanical or optical devices that do not need external power. They take measurements all the time and provide in general analogue signal output only.

The choice of sensor type selection depends on many factors like the chosen type of measurement, the expected resolution of the sensor's output signal, the number of measurements in space, the desired survival time of the array, the temperature exposure downhole, etc., and, last but not least, the cost for such a PDM observatory.

In today's PDM application one can observe a growing interest in following families of sensors:

- Seismic – geophones, hydrophones, accelerometers
- Geometric – mechanical tilt meter and pendulums
- geomechanical – strain meters
- environmental – temperature and pressure
- geochemical – gamma-ray, downhole sampler, pH meter

**Fiber-optic sensing**

Within recent years, continued developments in fiber-optic sensing have resulted in new sensor types with certain advantages over conventional electronic sensors, which previously have mostly been used for PDM.

For parameters like strain, pressure, or temperature, different downhole gauges based on fiber-optic sensors, like fiber Bragg gratings (FBG) and Fabry-Perot interferometers (FPI), are available. These are point sensors, which provide a record at the particular location where the sensor is placed, similar to most electronic sensors. Several sensors of this type can be placed and interrogated on a single optical fiber (multiplexing), and arrays including several tens of sensors can be created in this way.

In addition to this, fiber-optic sensing also includes methods where data can be recorded over very long distances of up to several 10s of km length with high spatial and temporal resolution. This is referred to as 'distributed' sensing, which is often based on the principle of optical time-domain reflectometry (OTDR). Exploiting different optical scattering mechanisms, several physical quantities can be measured. Methods successfully applied in PDM include distributed temperature sensing (DTS), distributed strain sensing (DSS), and more recently also distributed acoustic or vibration sensing (DAS/DVS).

The DTS method has been applied for on-line monitoring of well treatments like thermal stimulation, and to measure undisturbed formation temperatures by monitoring the decay of the thermal disturbance after drilling (Henninges et al. 2005). Vertical seismic profiling (VSP) and passive seismic monitoring can be performed using DAS or DVS measurements in boreholes. Here, superior data quality compared to other installation methods can be achieved (Daley et al. 2013) with permanent fiber-optic sensor cables cemented behind casing (Prevedel et al. 2008). This deployment method also simplifies simultaneous acquisition in multiple wells, which allows for cost effective high-resolution 3D seismic imaging (Götz et al. 2018).

Because no downhole electronics are required, fiber-optic sensors can tolerate higher temperatures compared to conventional electronic sensors. Nevertheless, at elevated temperatures of T > 150°C, the coating material of the fibers and effects like hydrogen darkening have to be considered, which can adversely affect the fiber performance. In order to mitigate such effects, specialty fibers with hermetic carbon/polyimide-coatings have been developed. During a field test in a high-temperature geothermal well in Iceland (Reinsch et al., 2013) have reported successful deployment of such fibers at temperatures up to 230°C over a period of 14 days, but different signs of degradation occurring after exposure to temperatures above 300°C.

**Data recording and data management**

Early downhole data acquisition systems were recording the measurements mechanically by means of a needle head writing analogue data in the downhole instrument on a rotating aluminum foil. The entire tool had to be retrieved to the surface before being able to remove the recording foil for manual data reading and interpretation. Today's acquisition systems for passive as well as active sensor arrays use a state of the art 24 bit resolution digital surface acquisition module for data collection and downhole sensor operation. Data are typically stored at surface on peripheral data storage devices and/or sent via mobile or copper line telephone communication, or via Internet data link to a central storage place for further processing.

Field solutions of data acquisition depend a lot on the measurement type and data volume, and can range from small PC-based systems to container-housed computer centers (Fig. 4.7.6) The specific measurement scope and data volume is typically driving the size of such a surface installation.

*Fig. 4.7.6: Recording container on top of the monitoring wellhead Tuzla-1 (GONAF)*

**ICDP experience**

The ICDPs Operational Support Group has, in the past, supported a fair number of permanent installations in deep and shallow boreholes all over the world. Many of them are still working today after > 10 years of downhole service. Some have been discontinued on schedule and some had premature downhole failure. Some of the highlight activities are listed below:

**GONAF, Turkey**

A Deep Geophysical Observatory at the North Anatolian Fault. Borehole Seismometer Network at the Eastern Sea of Marmara (Bohnhoff et al., 2017 A). Instrument array at 298 m with sensor (2Hz/15 Hz), at 225.64m one sensor (1 Hz), at 153.28 m one sensor (1 Hz), and at 74.89 m one sensor (1 Hz). 8 ½" borehole, static temperature < 40°C, max. depth 300 m. October 2012: successfully cemented to surface in the hole by means of a PVC pipe string. Cementing string cemented in the hole. All sensors in operation to date (Bohnhoff et al., 2017 B; Malin et al., 2018). (Fig. 4.7.6)

**SAFOD-Main Hole, USA**

The SAFOD project drilled and instrumented an inclined borehole across the San Andreas Fault Zone to a subsurface depth of 3.2 km, targeting a repeating micro earthquake source. It required sensors with very low noise floors and high signal fidelity at high sampling rates. The array included: Fiber-optic cable head, DS325 locking arm, Pinnacle high-temperature tilt meter, GERI DS250/DS150 adaptor, GERI DS150 65m interconnect, GERI DS150 seismometer, GERI DS150 65 m interconnect, GERI DS150 seismometer, GERI DS150 3m interconnect and weight bar. 8 ½” borehole, 125°C static temperature, max. depth 3998 m, longest operation: 2 months. September 2006: the array had to be recovered due to cable transmission failures and gas influx in the instrument packages.

**SAFOD-Pilot Hole, USA**
The SAFOD project drilled and instrumented a vertical pilot-hole (PH) across the San Andreas Fault Zone to a depth of 2.3 km, targeting earthquake sources from the San Andreas Fault prior to drilling the main hole (MH). The array included: 80 stations of P/GSI’s 3c analogue geophones. 8 ½” borehole, 115°C static temperature, max. depth 2347 m (7112 ft), longest operation: 16 months.
March 2004: the array had to be recovered due to an intersection of the MH with the PH trajectory and array failure as well as gas influx in the cable jackets.

**TCDP, Taiwan**
The Taiwan Chelungpu-Fault Drilling Project aims to monitor the major active fault where large displacements occurred during the 1999-Chi-Chi earthquake and to measure the physical properties and mechanical behavior, as well as to document the state of stress of the rocks above and below the fault zone over a long time period (Ma et al., 2006). The instrument array included: p(ressure)/ T(emperature) gauges, chemical sensors, U-tube sampling line and 7 stages of 3c seismometer (analogue) package. 6¼” borehole, 48°C static temperature, max. depth 1300 m, still operating. December 2004: successful installation on steel rope, cables and tube attached to rope with bands. Sensors in operation to date.

**DGLab, Gulf of Corinth, Greece**
Deep geodynamic laboratory aimed to investigate the mechanical behavior of active faults by means of downhole monitoring as well as the physics of earthquakes and aseismic fault motion. The instrument array included: pT gauges, optical strain meter, 6 pcs electrical electrodes and a 3c accelerometer package. 6 ¾” borehole, 31°C static temperature, max. depth 1001 m. September 2002: successful installation on wire line and outside the cemented casing. Sensors in operation to date.

**MALLIK, Canada**
Full-scale field experiments were conducted to monitor the physical response of the gas hydrate deposits to depressurization and thermal production stimulation (Dallimore et al., 2002). 8 ½” borehole, 15°C static temperature, max. depth 1150 m. Still operating. March 2002: installed sensor was a temperature gauge and an optical multimode DTS cable on the outside of a cemented casing string. Sensors in operation to date.

**Long Valley Exploration, USA**
The objective of this installation is to monitor over long periods of time the mid-crustal deformation in a magmatic-seismogenic dome of the Long Valley caldera in east-central California (Sackett et al., 1999). The instrument array included: 1c – strain meter, pressure gauge and 2 stages of 3c seismometer (analogue) packages. 6 ¾” borehole, 110°C static temperature, max. depth 2996 m, still operating. September 1998: successful installation on steel rope, cables attached to rope with bands. Sensors in operation, strain-meter was lost shortly after installation.

**Decision strategy**
There are many ways to collect data and information from a borehole and not all of them are to be considered as permanent downhole monitoring programs. They can spread from short-term logging and mud sampling to temporary installations of measurement sensors (Fig. 4.7.7).

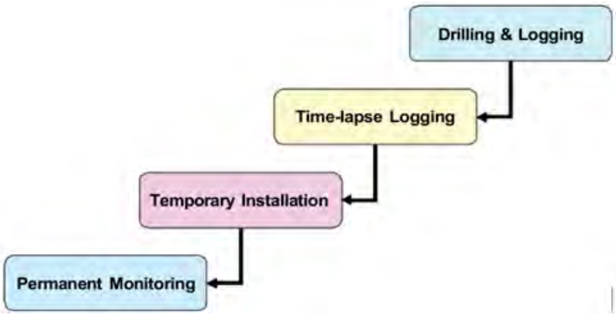


*Fig. 4.7.7: Evolution of measurement suites from standard borehole acquisition to PDM*

In today's terms a geophysical/geological monitoring installation is considered only a Permanent Downhole Monitoring (PDM) when a borehole is converted into a downhole observatory with a permanent installation of a sensor array in place. The final technical decision regarding measurement resolution and the type of sensor coupling to formation ultimately depends on the particular research tasks and the financial funds available. A guideline through this decision tree could be taken from Fig. 4.7.8.

**Continuous Fluid Sampling**
Water or fluid pumps can be deployed in a well as a submersible pump. One example is the Grundfos MP1 with a 2" diameter, made of inert material and specifically designed for pumping of contaminated/polluted groundwater for purging sampling and water quality monitoring from e.g., shallow boreholes. It has been specially developed for pumping of small quantities of water to be sent to the laboratory for analysis.

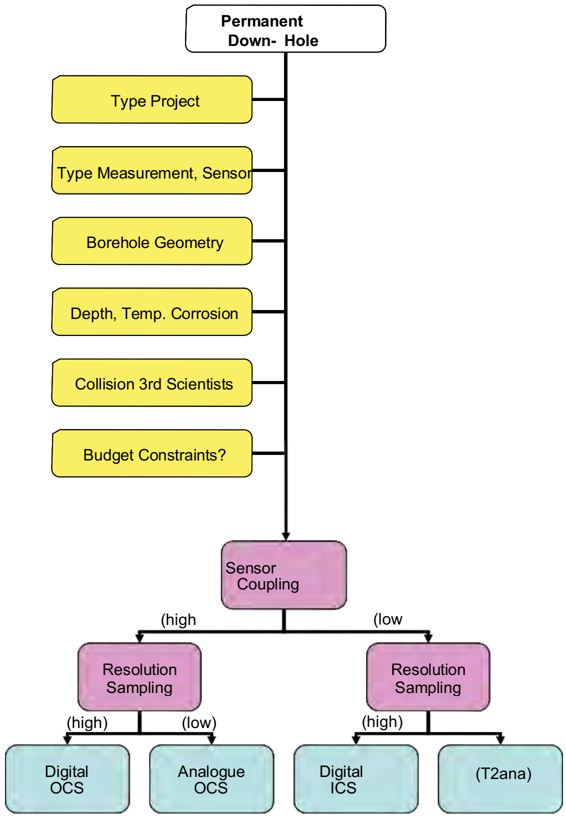


*Fig. 4.7.8: Decision strategy for the design and selection for a typical PDM system*

The pump performance is adjusted by means of the converter that controls the pump speed via the frequency. In this way a steady, air free water flow can be achieved. The MP 1 offers efficient purging of the well before sampling as a high pump performance is achieved when the frequency is raised. Maximum performance is at 400 Hz. The pumping system is not approved as explosion-proof. Power input is 1.3 kW at 3 x 220 V, 400 Hz and a maximum current of 5.5 A. The supply voltage is 1 x 220-240 V -15 %/+10 %, 50/60 Hz. Allowed maximum water temperature is +35 °C.

**Gas Membrane Sensor**
The Gas Membrane Sensor (GMS) is a device for real-time gas measurements and gas sampling in boreholes; it is patented for the continuous detection and analyses of gases in deep boreholes. The field capability of the system was proven at the CO2-sequestration pilot test site Ketzin, Germany, where it operated continuously

for 9 months in a 650 m deep borehole (Zimmer et al., 2011). It consists of a phase separating membrane element in combination with a special cable for installation in a borehole. The cable permits the conduction of the subsurface gas phase into an analytical device, (e.g., mass spectrometer, gas chromatograph, alpha- scintillometer) for real-time gas analysis at the surface and for the collection of gases for special investigations.

The method, developed and provided by the GFZ, allows for tracing of the concentration and composition of the gas phase down to depths of 2000 m and temperatures to 120°C.

Additionally, it is possible to obtain gases from deep reservoir horizons for detailed geochemical and isotope studies (Fig. 4.7.9).

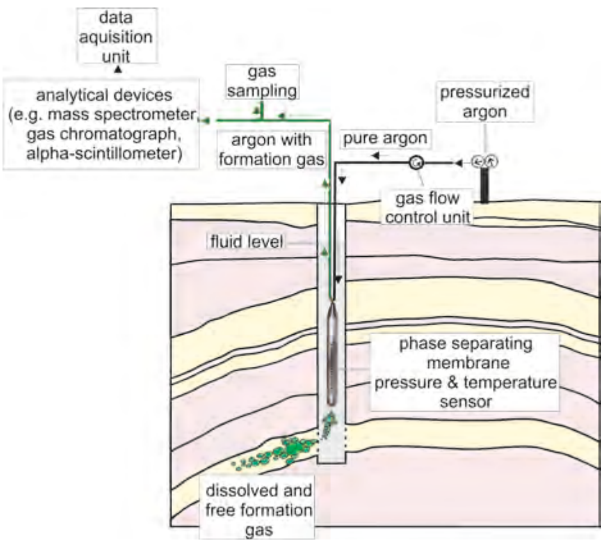


*Fig. 4.7.9: Mode of operation of Gas-Membrane Sensor (GMS) and experimental workflow*

The method uses a phase separating silicone membrane, permeable for gases, in order to extract the gases dissolved in borehole fluids, water and brines. The extracted gases mix in a prevailing argon stream provided from a pressure vessel and conducted via a capillary into the membrane element. Via a second capillary, the argon together with all gathered borehole gases is led back to the surface. Both capillaries are embedded in an especially developed borehole cable. At the surface, the gas phase can be analyzed directly and/or can be sampled for more detailed investigations in the laboratory.

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CHAPTER 5

# Training, Outreach, and ICDP Support

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## 5.1 INTRODUCTION

Scientific Drilling addresses fundamental questions of societal relevance including sustainable resources, environmental change and natural hazards. Moreover, scientific drilling projects are partly and, in many cases, even fully financed by science funding agencies and based on taxpayers' money. Therefore, Scientific Drilling actions and outcome must have an educational potential and must be made visible to the public, to media and decision makers in all levels. Furthermore, the recent discussions about new drilling-related technologies such as exploitation of conventional and unconventional gas resources, the utilization of the underground for carbon and hydrogen storage and tapping geothermal energy brought deep drilling into the focus of public's attention. In many countries in the world drilling occasionally has a negative connotation. Education and Outreach are therefore very important to ensure acceptance and must be an integral part of projects from the early stage, on.

## 5.2 TRAINING

Drilling is the ultimate method to retrieve matter from and yield information about the Earth's interior structure, processes and evolution, but unfortunately drilling is not a topic at most Earth science faculties of universities worldwide. Therefore, an important component of ICDP is the training of Earth scientists, engineers, and technicians in drilling-related know-how and technologies. ICDP offers a suite of different training courses, such as the annual scientific drilling training (see next paragraph), or specific technical course on e.g., geophysical downhole logging, Drilling Information System DIS, Online Gas Monitoring System OLGA, and core logging. PIs can even request ICDP training camps at their respective project drill site.

*Fig. 5.1: Training at the drill site*

**Training Courses**

The annual ICDP Training covers all relevant aspects of scientific drilling, including fundamentals of drilling technology, borehole measurements and interpretation, data management, sample handling and storage, and project management. The training courses are normally 3-5 days long and are free of charge for the attendees (Fig. 9.6.). The courses are held by a team of instructors who are specialists in their fields and with an extensive practical experience. Most of them have been involved in different ICDP projects worldwide. Specialists from the industry or scientific institutes will be engaged for special topics or individual courses if necessary. The current basis of the ICDP training is a set of eight courses covering the topics:

- Fundamentals of Drilling Technology
- Fundamentals of Sampling, Cores and Cuttings, On-site Sample Handling
- Drill Core Scanning and Logging
- Downhole Gas and Fluid Sampling and Monitoring
- Downhole Logging Fundamentals and Application
- Data and Information Management
- Project Planning, Management, Education and Outreach
- Downhole Seismic Monitoring

*Fig. 5.2: On site tool inspection during training*

The training can be adapted to specific topics, depending on the themes covered by upcoming drilling projects. ICDP publishes calls inviting interested individuals to apply for the annual Training Course on the Website, via Social Media and by ICDP Newsletters about six months prior to the event. PIs and scientists who intend to serve during planning and operation of upcoming projects are especially encouraged to apply for these training courses. Courses are preferably carried out at active ICDP drill sites and are taught by engineers and scientists who are experienced in scientific drilling. ICDP has allocated funding for invited participants to cover costs, such as travel and accommodation. ICDP encourages PIs to consider a comprehensive training course at or nearby any proposed drill site. This course will be jointly organized on project-related topics.

*Fig. 5.3: Specific training on Online Gas Analysis*

In order to support proponents, engineers, and scientists for their specific tasks within their drilling project we provide a number of training courses or workshops on request. For ICDP projects, we recommend to already apply for it in the workshop proposal and at least in the full proposal. These specific trainings include

- Drill Core Scanning & Logging
- Online Gas Analysis
- Downhole Logging

Please note that Data and Sample management training is mandatory 2-6 months prior to drilling. For this, PIs will be contacted directly by the ICDP-OSG Data Management Team.

## 5.3 OUTREACH AND CAPACITY BUILDING

Unlike oceanic drilling, continental drilling activities are visible to the local public and communicated through local, regional, and possibly national and international media before and during drilling takes place. Informing and involving the local public through public activities at any stage of planning and execution of drilling plays a critical role in the successful implementation of a continental scientific drilling project.

### Media

TV, radio and press can be duplicators of great importance for science and require attention by a drilling project manager in charge in any case. Proactive information to embed media about a project is usually the best approach to deal with public attendance. In addition, printed materials and web-based information can be used to reach neighbours and the community surrounding a drilling experiment. If goals, methods and risks are communicated in an open and transparent way, credit can be gained in the public (Fig. 9.1).

### Drill site visit

Acceptance by authorities, politicians and landowners is a decisive prerequisite for scientific drilling projects while drill rigs are landmarks attracting a great deal of local attention. Invitations to guided tours for school classes and open house activities will reach the neighbouring community best. Further target audiences for these and similar public outreach measures include funding organizations, stakeholders, politicians, media, educational organizations and the public at large.

An open house is a great opportunity for the public not only to have a look 'behind the scenes' but also for the project to generate positive public and media interest and to address potential negative prejudice upfront. Furthermore, it allows emphasizing scientific aims and societal benefit.

*Fig. 5.4: Interview at the drill site*

### Open House activities - Action items

- Arrange date and terms with drilling contractor, permitting authority and landowner as early as possible
- Make sure that an open house will neither interfere with drilling operations nor jeopardize safety
- Inform local and regional media (press, radio, TV) to invite the local community, local politicians and landowners
- Invite neighbours, schools and locals via flyers at public places
- Do not forget to invite representatives of funding agencies, authorities, politicians and other decision makers
- Announce the 'Open House' on social

media (see next paragraph)

- Provide information on how to reach the drill site, about nearby service facilities and infrastructure (next gas station, restaurant, supermarket, mobile phone reception)
- Prepare sufficient parking space for the visitors´ cars at the drill site
- Keep a sufficient number of hard hats and, if needed, safety goggles and safety boots ready
- Display drilling in action such as rotating drill strings, circulating drilling mud but avoid a visit during risky operations
- Organize group tours over the drill site by guides familiar with drilling techniques and scientific objectives
- Tours can be guided preferably by PIs, their drilling supervisor and possibly personnel of the drilling company (Fig. 9.2)
- Pay special attention to school classes and their teachers as an important target group for science outreach
- Display informational materials such as project flyers and organize give-aways
- Get in contact with OSG for ICDP brochures, flyers and other media on scientific drilling

**Project website and social media**

ICDP will create a project website for each project as soon as a workshop proposal is approved by ICDP. As part of the MoU (Memorandum of Understanding) between ICDP and the project PIs, the project is encouraged to provide daily news during the operative phase for this website which mostly serves as information platform for the science community. In addition to the specific ICDP project website, social media (SM), such as Facebook, Twitter and blogs, have extensive potential of sharing information to a general audience at very little monetary costs. It will be necessary to keep such media regularly updated during the operational phase of a project with emphasis on project success, but not drawbacks.

*Fig 5.5: A guided tour of the drill site helps visitors to understand the drilling process*

Attracting a broader readership outside science requires content that is not too complex for the average person, full of jargon or acronyms, or might cause adverse attitudes against the drill project. Social media can serve as a platform to share information about other project-related outreach activities.

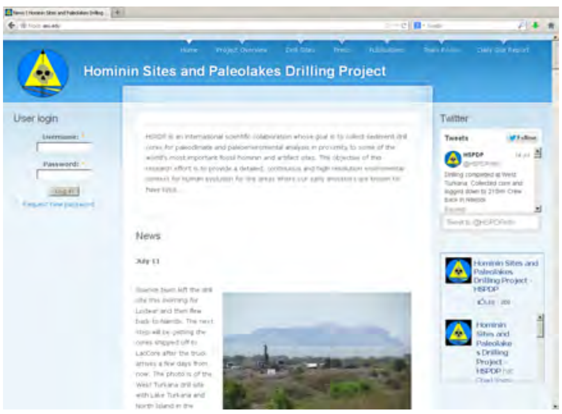


*Fig. 5.6: Social media page of the Hominin Sites and Paleolake Drilling Project in Kenya, Ethiopia*

A few general guidelines should be observed on posting messages from ICDP scientific drilling projects on the internet:

A message consists of text (including headline and subtitle) and possibly additional media (images, videos, audios, documents, links to relevant sources). The message is a text that gives the reader an idea of what is going on, what happened since the last post and should always include a minimum set of metadata such as:

- title
- date and time
- name(s) of the author(s)

Additional media should have

- a short caption which directly refers and describes the content shown
- including credits to the creator(s)
- if possible, the media should be shown in a preview style like a thumbnail and/or a link to the media to open or to enlarge it in a separate browser window or lightbox
- in general, a download of these media should be allowed

Usually, a larger number of collaborators are involved in an ICDP scientific drilling project. Social media (topmost twitter and facebook) are an easy way to upload content from many different distributed sources and present it in the way described above. But it also allows adding content on-the-fly easily and quickly. Therefore, it is very important that a responsible editor should supervise and overlook these proceedings. Collections of excellent images without a context to a general message, without captions explaining the image in few words do not help readers/viewers, who, although at times basically involved, have no deeper insight into the particular event.

Beside the credits to the creator(s) the content of a social media page or posts for an ICDP scientific drilling project should be made available for re-use through a Creative Commons (CC) license:

- allows to modify it for non-commercial use applying the same CC license conditions
- allows to modify it, commercial use is allowed by applying the same CC license conditions

See more about Creative Commons (CC) licenses at: https://creativecommons.org/. Also see the corresponding license agreements and regulations of the particular social media provider you are using.

**Press release**

A press release (or, more general, media release) is a written or recorded communication directed at members of the news media for the purpose of announcing something ostensibly newsworthy. Typically, they are mailed, emailed or faxed to assignment editors at newspapers, magazines, radio stations, television stations, or television networks. A press release can be useful to generate public interest in your project in particular at the beginning of drilling operations. It generally serves to answer questions of what, why, when, where and who. It can be organized such as a pyramid with key information at the top and more details at the base. The less relevant information at the end of the body text will possibly be shortened by media writers if used for a newspaper article. The text should consist of 4 to 5 paragraphs with a word limit ranging from 400 to 500 followed by contact information and web link. High-resolution photos available for media use should be provided as well. Press officers of university associated with the project will help to prepare and publish a press release.

**Video documentation**
A well-produced video documentation on a drilling project serves as science outreach tool presented at schools, universities, meetings of all kinds, conferences and to the general public, possibly also included on nationally syndicated broadcast services (TV, Radio, etc.). A short trailer (1-2 min.) is especially useful for online video platforms such as Youtube. On the ICDP website several science movies on ICDP drilling projects are displayed. The videos were produced with financial support through ICDP and other co-funding agencies (Fig. 5.7). Funding for the movies was granted based on a proposal to ICDP. The Operational Support Group will provide information about video production companies.

**Outreach to the science community**
ICDP unites a growing, large science community of about 3000 individuals all over the world. This diverse Earth science community engaged in scientific drilling spans many very different fields of expertise whose protagonists do not communicate with each other automatically. Sharing information about the program and promoting interaction is therefore a must. ICDP carries out Town Hall meetings at international conferences such as AGU and EGU to inform the scientific drilling community about the status of the program and current or upcoming scientific drilling activities. These meetings are a good opportunity to make scientists aware of upcoming drilling projects and the possibilities for collaborations. PIs and leading scientists from current or future continental scientific drilling projects are invited to use this occasion to communicate and deliver important news or messages to the community.

*Fig. 5.7: Video documentation at drill site (Koyna, India)*

Scientific sessions at major conferences are another tool to address the science public. ICDP and IODP/ECORD regularly carry out a joint scientific drilling session at the EGU meeting, where new technical developments and scientific results about completed and current drilling projects are presented. Conferences and workshops can be used to increase awareness through outreach material (flyers, posters, brochures). At large Earth Science conferences a booth is often set up by ICDP in partnership with IODP to provide information and display instruments and videos on operations, technologies and projects.

The journal Scientific Drilling is an open access journal jointly issued by ICDP and IODP and published semi-annually by COPERNICUS Publications. Scientific Drilling (SD) is a multi-disciplinary journal focused on bringing the latest news about scientific drilling – especially scientific-technical expedition-reports – to the community. It delivers peer-reviewed science reports from recently completed and ongoing international scientific drilling projects as well as on engineering and other technical developments on ocean and continental drilling, workshops, progress reports, and includes short news sections for updates about community developments.

As part of the MoU, PIs are requested to submit a workshop report to SD after the workshop and a science report after drilling was completed. Both reports are to be published in one of the two volumes of SD issued after the workshop was held respectively drilling was completed. For submission details see the Scientific Drilling website.

*Fig. 5.8: The ICDP-IODP Open Access Journal 'Scientific Drilling' is published semi-annually*

### 5.4 COMMUNICATION MANAGEMENT

'The news media could be described as one of the worst ways to explain science, given its fast turnover, tight deadlines and space constraints. However, there are very good reasons for using this as a medium to get your messages about science across' (www.sciencemediacenter.org).

Popular media, such as television, radio, newspaper, magazines, and internet blogs, play a vital role in communicating science to the public and are critical to the process of dialogue and engagement. Today the vast majority of ordinary people gain knowledge about scientific and technical progress from news delivered by popular media and form their own opinion based on the provided information. Scientists are in a position of having a professional responsibility to communicate their research with popular media as the major pathway to reach out to the public and stakeholders.

However, the interaction between scientists and media representatives or journalists is often described as difficult and unsatisfying – from both sites (see e.g., Maillé et al., 2009, and references therein). A different perception of their specific role in the process of communicating science to the public sometimes results in struggle for control over the communication process (Peters, 1995). It is therefore crucial that scientists understand the role of media and how media outlets operate to avoid misunderstanding by the media and miscommunication to the public.


*Fig. 5.9: Media briefing at the drill site*

Journalists would define themselves as (i) translator to popularize science to the general public and (ii) bearer of society's questions. Their job is not to represent scientist's interest. Journalists are in the business of defining and selling news and are in competition with other media representatives. They also want to entertain and, depending on their self-conception, also present critical or even polemic viewpoints. According to their understanding, the scientist's role is to deliver information and facts, not to put them in a societal or other relevant context. Being under time constraints, it is difficult for journalists to deal with complex settings and situations that cannot be described in a simple 'black or white' scheme. This may result in oversimplification and inaccuracy.

The following guidelines have been developed to provide scientists involved in ICDP projects a helping hand when receiving requests for interviews or when they feel a need to inform the public about important findings of their research or about critical events, e.g., accidents or delays.

**Before any contact with media**

- Coordinate your media interaction with all parties involved in the project beforehand
- Any statement to the press about the project, its aims and objectives, progress, success and challenges, should be issued by the Principal Investigators or somebody on behalf of them (e.g., an external consultant/company person for technical and non-scientific questions)
- If others than PIs (on-site scientists, students) are contacted by media representatives, they should always refer to the PIs as contact partner for the media
- The media officer of your organisation should be informed about any approach by media. You can always ask him/her for advice if you are not familiar with communicating with media and interviews.
- Coordinate with the other PIs what message should reach the public and what information should remain confidential. If any information is confidential do not write about it in emails to other PIs as such emails tend to get forwarded and then develop destructive power. Instead of writing, talk on the phone to your colleagues about potentially critical information.

**Preparation for an interview**

- Think positive! Consider an interview as a great opportunity to spread the word about your project and inform the public
- Get to know the medium that requests an interview. What is their target audience and which standpoints do they take?
- Ask before the interview if other scientists will be interviewed on the same topic
- Consider that a request for an interview about an inoffensive topic may serve as a door opener to ask problematic questions in front of a rolling camera
- An interview is a stress situation for both the journalist and the scientist. You can lower your stress level by preparing yourself with 2-3 statements

that you want to deliver to the public. Have your facts ready at hand.

- In general, interviews on scientific issues are less problematic than interviews on e.g., politics or finance. The usual attitude of science journalists is friendly and pro-science (for other cases, see below).
- Be aware that media outlets are under considerable financial pressure, meaning that journalists either do not have much time to prepare for an interview or they are not science journalists but interns or rookies. Therefore, don't be annoyed by seemingly uneducated questions.
- It helps to write down three key messages you want to bring across (writing in longhand is more helpful than typing)

**During the interview**

- Make yourself aware that your audience is the public probably including those taxpayers funding your scientific drilling project.
- Underline the relevance of your research for the general public. Your audience is not the media representative or your scientific community.
- Make your statements short, simple, clear and in a generally understandable form. Avoid acronyms and scientific language. Imagine yourself explaining your project to your grandparents.
- Make clear in the interview if your results are at preliminary stage, yet have to be published in a peer-reviewed journal, or differ from those of other scientists.
- Description of methodology is important for the science community, not for the general public.
- Be self-confident. Remember that the media choose you as interview partner because you are the expert in the respective field.
- Dress neatly and avoid wearing anything that may be distracting on screen, e.g., brightly patterned shirts (Moiré) or cartoon ties.
- Avoid referring to previous questions ('as I said before') because this makes it harder to edit.
- Don't be afraid to repeat whatever key messages you want to convey.

**Risk communication in crisis situations**
Communication about drilling is a critical issue. People tend to select and interpret information in order to support their existing worldview and drilling received some negative attitudes after some disasters and accidents in the past (Deepwater Horizon disaster in the Gulf of Mexico, drilling-induced seismicity and the on-going debate about fracking).

- Be prepared for questions about drilling safety and risks and take questions about risks and hazards seriously
- Avoid appearing arrogant and all-knowing
- Be aware that the scientific definition of risk (statistical probability of an event x hazard potential of an event) does not match with ordinary people's thinking about risks. One way of putting risk into a more understandable context is to make comparisons between the actual risk and one that is more familiar to the people.
- For video interviews with potential negative content (e.g., about accidents, unforeseen incidents): try to avoid lurid reporting. Look for a neutral background with no victims or ruins, no company/project logos, etc.
- In a crisis situation, ask your media officer if a press release prior to an interview would be beneficial. You probably don't want to attract additional attention during a crisis situation. On the other hand, issuing a press release together with your media officer before media requests can give

you some momentum and control about the next steps of the communication process.
- In cases of critical events or crises, e.g., accidents, you should always include your media office. Don't shy back from asking them to be present during the interview. It also helps to rehearse interviews with your media officer.
- If there are casualties, don't hesitate to show your concern for the injured or dead people and their families. Everyone will understand that you are nervous or reluctant on such occasions.
- It is perfectly okay to admit that you do not have all facts in a crisis situation.

Consider the following phrases for your interview in a crisis situation as do/do not:

**Say:**
- The following has happened…
- We are working hard to find a solution (or: We are working hard to investigate what led to the situation)
- Next steps to be taken are…
- Right now, we can't tell you more, but additional information will be provided as soon as we have it (avoid specific dates)
- I can see your point

**Don't say:**
- You don't understand
- We don't understand
- I fully agree with you/your point
- You are wrong
- The subject was blown up by the media
- We need more time
- We will provide more information by tomorrow (or any other exact date) as you are then under some obligation to deliver at this point
- No comment

**Recommended further readings**

Maillé, M.-È., J. Saint-Charles and M. Lucotte (2009). The gap between scientists and journalists: the case of mercury science in Québec's press. Public Understanding of Science 19(1): 70-79.

Peters, H.P. (1995). The Interaction of Journalists and Scientific Experts: Co-operation and Conflict between Two Professional Cultures, Media, Culture and Society 17: 31-48.

Peters, H. P. (2013). Gap between science and media revisited: Scientists as public communicators. Proceedings of the National Academy of Sciences of the United States of America, 110 (Suppl 3), 14102–14109. doi.org/10.1073/pnas.1212745110

MESSENGER (Media, Science & Society - Engagement & Governance in Europe Guidelines) Guidelines for Scientists (http://www.sirc.org/messenger/messenger_guidelines.pdf)

http://www.sciencemediacentre.org/wp-content/uploads/2013/08/SMC-Why-Engage-2015.pdf

## 5.5 SCIENTIFIC-TECHNICAL COLLABORATION WITH OSG

The principal task of the OSG during the operational phase of ICDP drilling projects is to support the scientists involved in the project in the acquisition and management of on-site data. This is done by providing equipment and instructions on its use (e.g., core scanning and logging, gas analysis), performing measurements (downhole logging & monitoring, fluid sampling), and training and support in data management (Drilling Information System, DIS). The on-site data lay the foundation for further scientific investigations by the project scientists. The tasks of the OSG generally do not include performing measurements for OSG staffs´ own scientific purposes.

It is a prerequisite for the funding of drilling projects by ICDP that projects should cover the broadest possible spectrum of relevant scientific issues. However, not all projects funded by the ICDP are able to fully exploit the scientific potential of their drills on their own. Besides staffing issues, reasons for this can be 1) lacking knowledge on new or unknown investigation methods or 2) on the scientific potential of new interpretation of already existing data for the drilling project. The latter (2) may apply, for example, to the scientific interpretation of geophysical borehole measurements (downhole logging).

In lacustrine sediment drilling, the geophysical logging data are often only used to establish depth correlations between drill core and drill holes, but is not further interpreted scientifically. However, beside its value for depth correlation, data from downhole logging also provide significant scientific insights for paleoclimate reconstruction, e.g., on glacial/interglacial cyclicity. The further (1) is relevant to the ICDP online gas analysis of drilling mud OLGA, a relatively new method which, in several ICDP drilling projects, provided important information on fluid compositions and fluid pathways in the subsurface, ideally in combination with downhole fluids and gases taken by the ICDP downhole fluid sampler.

In order to exploit the scientific potential in the field of fluid and gas geochemistry as well as borehole geophysics as comprehensively as possible, the OSG offers cooperation in these subject areas within the framework of a scientific collaboration. The impetus for scientific cooperation between the OSG and the project beyond common operational support should be initiated by the projects. The cooperation between the project scientists and OSG covers the entire course of the experiment, starting with planning and logistics, joint execution of the experiment, evaluation of the data and joint publication. The participating project scientists are thus given a comprehensive insight into the implementation of the experiment. The know-how thus gained is intended to support future own research in the corresponding research field.

**Workflow OLGA**

If science teams are interested in a scientific collaboration in the field of borehole fluid and gas geochemistry, they are kindly invited to contact the OSG as soon as a concrete time frame for the drilling has been determined. This helps to ensure that the necessary instruments can be made available for the envisaged period. The instruments will then be reserved for the project at the requested time.

For ICDP’s OnLine Gas Analysis of drilling mud OLGA, the project has to provide the staffing to oversee, run, and maintain the experiment on site, ideally a PhD student or postdoc with an interest in geochemistry and a minimum of technical understanding. Once the OLGA instruments are set up and operational, daily standard maintenance does not take more than 2 hours per day. The scientific equipment is provided for the projects for the duration of the experiment on the basis of a loan agreement. No user fee is charged, the only costs for the project are transport and a small fee for consumables. However, the project is liable for damages caused by negligence and loss. Taking out an insurance can be useful here.

In order to ensure that the OLGA experiment is carried out successfully by project scientists, they are trained in the use of the instruments by the OSG. The training can either take place at the GFZ in Potsdam, Germany, ideally a few weeks before drilling begins and e.g., in combination with other training measures (DIS, MSCL, Optical Core Scanner), or on site immediately before drilling begins. Experience has shown that the time at the drill site shortly before drilling begins is relatively stressful, which can make effective training difficult. Therefore, training at the GFZ is, in principle, the better option. The costs for such a training are shared between the project (travel costs) and ICDP (accommodation, food, local transport).

The OLGA experiment is set up on site by the responsible scientist and the OSG a few days before spud in. It takes about 3-4 days to set up, including all calibrations. During drilling operations, the measurements are performed by the responsible scientist on site. Online access or regular transfer of the raw data to the OSG helps to ensure that the experiment is conducted correctly. If necessary, the OSG provides support during the execution of the experiment via e-mail, videoconference or telephone. Only if repairs are required that cannot be carried out by the on-site scientist, an OSG representative will travel to the site in person.

The data evaluation includes, first of all, the creation of gas depth profiles to identify fluid inflow zones in almost real-time. Possible further supporting measurements on gas samples (e.g., noble gas isotopes) can be arranged at the GFZ and can be conducted either by the OSG or project scientists. These measurements do not involve any additional costs, but if they are carried out by project scientists, the costs for their stay at the GFZ (travel, accommodation, meals) must be borne by the project.

The use of the OLGA system implies scientific collaborations between the OSG and a science team member (STM) of the drilling project and should result in a joint publication (Podugu et al., 2019, Wiersberg et al., 2020).


*Fig. 6.5: Possible knowledge transfer workflow in ICDP projects*

**OSG downhole logging support**

The OSG offers support for downhole logging in ICDP projects. The support encompasses evaluation and support of planning and management of downhole logging programs within ICDP proposals, the actual performance downhole logging, and the scientific interpretation of the acquired data. OSG's level of assistance in preparing downhole logging programs primarily depends on the requests of the ICDP project PI's. It can be comprised of:

- helping to develop or optimizing a downhole logging plan that accommodates the scientific targets and the given project conditions

- review of offers and quotations of potential logging service providers (time and availability of equipment & expertise)
- support with the equipment acquisition
- cost assessment.

If desired, the OSG can carry out downhole logging measurements with its own logging equipment suitable for most ICDP logging conditions. The close in-house cooperation with other OSG experts (drilling, core handling and data management) assures smooth and optimized operations. If desired the OSG may also assist in the management and oversight of logging activities of external providers.

OSG logging can complement any other logging services or carry out all the downhole logging of a project. Costs are minimized and are comprised only of a very low tool utilization fee, travel/transport costs of personnel and equipment and insurance of the equipment. No depth or measurement charges and personnel costs are imposed as these are covered by overall ICDP funds. The low costs enable downhole logging even for ICDP projects with a low budget.

OSG participation in downhole logging operations is not mandatory. OSG consulting is free of charge for ICDP projects. OSG cannot and will not compete with commercial logging service providers. OSG preferably recommends the use of commercial services if these provide more parameters, higher resolution, more powerful, advanced methods, and if the project budget allows.
Following the actual downhole logging campaign, a logging job report is compiled comprising the operational details: logging tools used, logging depth intervals, depth reference, number of runs, problems encountered, statistics, and first findings, if possible. Logging data itself are usually not handed out on-site but only later after depth correlation and environmental corrections have been applied at the office.

**OSG log interpretation support**
Some ICDP projects use the acquired downhole logging data only for core depth correction and for filling gaps in sections with core loss. In these cases, the downhole logging data are not further evaluated so that the high-quality logging data are achieved with great effort but the full potential of the data is not fully utilized.

The under-utilization of the downhole logging data is usually because individual ICDP project teams are missing a logging specialist to analyse, interpret and undertake research using the available logging data. The downhole logging team of the OSG provides geoscientific analysis and interpretation of downhole logging data. In case an ICDP project has no resources to analyse and interpret the logging data, the OSG logging team can perform the analysis and interpret the borehole measurement data, thereby adding value to the ICDP project. Some of these analyses have to be combined with additional data (i.e., core/cuttings data, seismic data) from other research teams. In such cases the OSG logging team becomes member of the project's science team and gets access to the complete dataset of the ICDP project.

The OSG logging analyst will work on the logging data as part of a research project that will result in publications, where logging is integral to achieving an expedition’s objectives. The interpretation of downhole logging data and the results will be submitted to the PIs for approval and then be published according to the Science Team plan.

In case the ICDP project team already includes an individual or a group with an interest in a specific logging dataset but not in the other available collection, the OSG logging specialist can be involved in analysing the other pool of borehole logging data according to the PIs and the aim of the ICDP project. Together with the team, the entire pool of logging data can be integrated adding value to the scientific output of the project. An additional aspect of the involvement of a logging analyst concerns the data quality control of downhole logging measurements. During the logging campaign technical problems with tools or the well may occur but remain unrecognized during the acquisition phase. Afterwards, the logging analyst can perform quality control of the data set (e.g., the orientation of the tool, value of the data reasonable) and identify any artefacts in the logs.

Lake Projects are an outstanding example where downhole measurements can complement core losses or poor recovery. Often the ICDP Lake project team does not have a specialist or a specific interest in using downhole geophysical measurements. Together with the OSG, the OSG can design a scientific plan on how to utilize the logging data. Recent approaches that use the downhole logging data focus on:

1. Reconstruction of the history of lake records covering the glacial-interglacial cycles data without the high-resolution data derived from core analysis. The response of depositional environments to the climatic variations is periodic in time and these climatic variations are embedded on sediments and recognized as variation in their physical properties (e.g., grain size, mineral type, mineral abundance especially for clay, organic matter), which are also detected by downhole logging measurements.
2. Identification of glacial/interglacial cyclicity merging the downhole logging data (e.g., GR, SGR, MSUS) and mineralogical analysis. Linking the abundance and the lack of e.g., clay minerals in core samples with the downhole logging data, a relationship between geological history of the lake and climate change processes can be recognized reflecting glacial/interglacial climate cyclicity.
3. Facies characterization from downhole logging data by cluster analysis. Downhole logging data of lacustrine sediment records can be analyzed in terms of sediment evolutions and lithological changes.
4. Core-log seismic integration allows relating physical properties of reflectors found in the core records to seismic profile in order that the spatial and temporal extent of these reflectors can be traced well beyond the borehole. In the course of this process, geophysical logging data acts as an intermediary in achieving this goal. CLSI allows integrating core measurements, logging data and seismic data, which differs in spatial resolution and rock properties.
5. Combination and integration mud gas data (OLGA), core and logging data, as successfully done at the ICDP COSC-1 project.

## 5.6 THE ICDP EQUIPMENT POOL

Most of the research in continental scientific drilling projects is performed after drilling operations in labs. However, there are investigations that, for several reasons, need to be executed during drilling. This includes:

- on-site investigations to provide rapid information for aiding decisions, e.g., core/borehole correlation studies for depth matching or the identification of target depths related to formation testing, sidewall coring, or side tracking
- studies (downhole logging, fluid sampling) requiring access to open hole
- studies on ephemeral properties and on microbiota
- studies providing a fundamental database for all subsequent research activities (e.g., lithological log)

Given the limitations in manpower, time and space at most drill sites and the rough on-site conditions (e.g., fluctuating power supply), the set of scientific on-site investigations should be limited to the absolute minimum. Generally, sampling should be performed after completing the drilling operations, e.g., during sample parties in core repositories. Some studies, however, require sample material to be obtained immediately after fresh core arrives at the surface, e.g., microbial sampling for deep biosphere studies, or any sampling of material that would otherwise suffer decay, degradation or contamination at the surface. Furthermore, sampling of fluids and gases from downhole fluid sampling, drilling mud gas and core voids require immediate action at the drill site. The sampled material must be stored immediately after sampling under special conditions regarding temperature and pressure (e.g., vacuum) to avoid degradation or contamination. On-site sampling must be requested from and approved by the Principal Investigators prior to spud-in.

**On-site science in lake drilling**

During lake drilling projects, where mostly soft sediments are retrieved, the drill cores remain in their respective plastic core liner until they reach the designated core repository, which naturally limits the applicable on-site research to non-destructive methods which penetrate through the core liner (e.g., Magnetic Susceptibility measurements on un-split cores conducted on with multisensor-type scanner). Core opening, washing, sawing, lithological description (except of core catcher material), optical and X-ray based investigations and sampling will therefore be conducted after drilling.

For most lacustrine and lake sediment drilling, the completeness of a core record from a drill site is crucial, which can be provided on site by core-borehole correlation. For this purpose, magnetic susceptibility and gamma density measurements on drill core and downhole logging are the most common tools. Gamma density measurements require logging with radioactive sources that is logistically challenging and therefore not provided by the OSG. Magnetic susceptibility, obtained from drill core by core logging (using a Multi Sensor Core Logger-MSCL), in combination with downhole logging therefore builds the base for site-to-site core-borehole correlation, and is thus strongly recommended for lacustrine drilling projects.

**On-site science on land**

In contrast to lake sediment drilling, where several holes are drilled at one site for the completeness of a sediment record, land drilling projects with a multi-hole approach follow different objectives. The purpose of two or more holes (Monitoring Hole/Pilot Hole/Main Hole) at one site is here i) to get background information on the lithology for later Main Hole drilling, ii) for seismic or hydraulic cross-hole investigations, and iii) for long-term monitoring. While some ICDP drillings have retrieved an almost complete core record by wireline coring (e.g., Songliao Basin, Oman, COSC, Donghai, HOTSPOT, Barberton), other projects (e.g., SAFOD, Mallik, IDDP) recovered only spot cores from target horizons. Depending on the drilling techniques used in scientific drilling projects (slimhole or oilfield-drilling), rock sample types (cuttings or core), and project objectives, different on-site investigations are recommended for aiding rapid decisions, including the lithological description of core or cuttings, drilling data (lag depth, ROP, WOB, time in/out, drilling mud volume etc.), MWD/LWD (if available), core scanning, core and downhole logging, and on-line gas monitoring (if available).

Mining drilling mostly delivers continuous core that can be opened, described and measured at the drill site (core scanning and logging). The lithological description of core, core scanning, and downhole logging build the data base for making decisions on site and furthermore provide an important dataset for later sampling parties.

*Table 5.1: Different drilling methods and sizes for the various drilling scenarios as part of planning and conducting drill experiments on land and on lakes*

| Drilling Technique | Lake Sediment Drilling | Continuous Coring/ Mining drilling | Rotary Drilling/ Oilfield drilling |
|---|---|---|---|
| Borehole Diameter | PQ, - HQ - NQ (123 – 95 – 76 mm) | PQ, HQ, NQ (123 – 95 – 76 mm) | 26-22-17 ½ -12 ¼ - 8 ½ - 6 ¼ inch |
| Average numbers of holes per site | >1 | 1-2 | 1-3 |
| Coring technique | continuous wireline coring | continuous wireline coring | Roundtrip, spotcore |
| Most common sample type | core | core | Cuttings, spot core, sidewall core |
| On-site core handling | Core remains in liner. Marking, packing, labeling. | Opening, cleaning, sawing, description, marking, packing, labeling | If applicable: opening, cleaning, sawing, description, marking, packing, labeling |
| On-site core investigations | Core Logging (MSCL) | Core Logging (MSCL), Core scanning | Core scanning |
| On-site lithological description | - | Based on core | Based on cuttings |
| Use of drilling data | Limited, data not continuously recorded | Limited, data not always continuously recorded | Continuously recorded (RoP, WoB, Lag Depth….) |
| Other methods | Downhole Logging | Downhole Logging | Downhole Logging, MWD/LWD, OLGA, Downhole Fluid Sampling |
| Further borehole use | - | VSP/MSP, long-term monitoring | VSP/MSP, Testing, long-term monitoring |

Most projects applying oilfield-drilling technique have to deal with cuttings: small rock chips of variable size dragged out of the borehole by circulating drilling mud. Drill core is only available from few target horizons, if ever. The lithological description on-site is therefore based cuttings analysis. In contrast to mining drilling, continuous technical drilling data are often available in oilfield drilling which are important for e.g., cutting analysis (lag depth) and for making on-site decisions. As for the other drilling techniques, downhole logging is performed during drill stops, but oilfield drilling also allows integration of logging tools to the Bottom Hole Assembly (BHA) (MWD, LWD) which can deliver data in almost real-time. Cutting analysis can prove in almost real-time if side-tracking is successful.

**Available tools**

Instruments and tools acquired through ICDP grants are integrated and maintained in the ICDP Equipment Pool by the Operational Support Group (OSG). Project scientists can operate a number of these scientific instrument sets at drill sites. The tools will be provided to ICDP projects on request. Requests are to be made as early as possible (first-come, first-serve policy). The OSG usually introduces on-site scientists of individual projects to the use of these devices. The instruments listed below have been used at several drill sites in support of the core handling procedures and the initial core description.

**Multi-Sensor Core Logger**

The Multi Sensor Core Logger (MSCL, Geotek) measures a suite of geophysical parameters rapidly, accurately and automatically on sediment or rock cores. The rugged nature of the equipment makes it suitable even for use in a laboratory container on-site (Fig. 8.1). Core sections up to 10 cm diameter and up to 1.55 m long can be logged at spatial intervals as low as a few millimetres. ICDP's Multi Sensor Core Logger is configured to measure:

- P-wave velocity (250-500 kHz piezo-electric ceramic transducers, spring-loaded against the sample. Accurate to about 0.2%, depending on core condition
- Gamma density (bulk density): $^{137}Cs$ gamma source in a lead shield with optional 2.5 mm or 5 mm collimators. Density resolution of better than 1% depending upon count time
- Magnetic susceptibility: Bartington loop sensor of 100 or 120 mm diameter, or point sensor (on split cores) giving 5% calibration accuracy over two ranges: $1 \times 10^{-6}$ and $10 \times 10^{-6}$ cgs.
- Natural gamma radiation: three 3″ × 3″ NaI(Tl) detectors housed in 6″ diameter lead shields generate 1024 channel spectra to be used for calculating elemental yields for K, U and Th.

*Fig. 5.9: Multisensor core logger in field lab*

Data can be obtained from whole core sections and core sections contained in plastic liners. More details on instrument functionality, calibration and so on can be found under: http://www.geotek.co.uk/products/mscl-s. Additional information on typical parameters measured for drilling projects:
www-odp.tamu.edu/publications/tnotes/tn26/TOC.HTM.

**Prerequisites for core logging**

MSCL measurements are essential for depth matching of drill core from lake and soft sediment drilling. If the ICDP owned scanner is used, space must be provided in a laboratory trailer, container or similar makeshift lab space. The size of the MSCL is

4.7 × 1.4 × 0.9 $m^3$ (l × h × w) plus some additional space (0.6 × 0.6 $m^2$) is required for the electronics bench. Trailer space can be utilized alongside other instruments (e.g., Core Scanner) if no liquids (e.g., water) are used in the trailer. Power supply (220 V) must be buffered or electrically disconnected and independent from rig power (e.g., external generator or public power supply). The power input of the MSCL is ~2000 VA.

Scientists should state in their full proposal to ICDP that they are interested in utilizing the ICDP MSCL. Requests to use the devices are to be made to OSG as early as a drilling timeline is fixated. In case of overlapping requests, ICDP's OSG will try to organize one device from other sources for the group, which placed the request at a later time. The equipment will be provided on the base of a lending agreement. Shipping costs, custom fees, etc., are to be covered by the project.

Scientists in charge of operating the MSCL have to be designated by the project. ICDP will not provide the manpower to operate and maintain the experiment during drilling but technical support if necessary. Training of on-site operator(s) can be conducted by OSG in Potsdam some weeks prior to drilling operations start. Costs for training are to be shared between the project and ICDP. The on-site instrument operator with OSG support will assemble the experiment immediately before spud in.

**Optical Core Scanner**

ICDP provides one DMT Core Scan3 line scanning device. The instrument allows optical high-resolution scanning of whole or slabbed hard rock drill cores and soft rock half cores in diameters from 4 to 22 cm and maximum length of 1 m. The device can also be used to scan cuttings and other sample specimens in close-up views. Additionally, the DMT Core Scan3 is capable to acquire core box overview scans. Image sizes are up to 25 MByte with a resolution of 5 - 10 pixel/mm = 127 - 254 dpi.

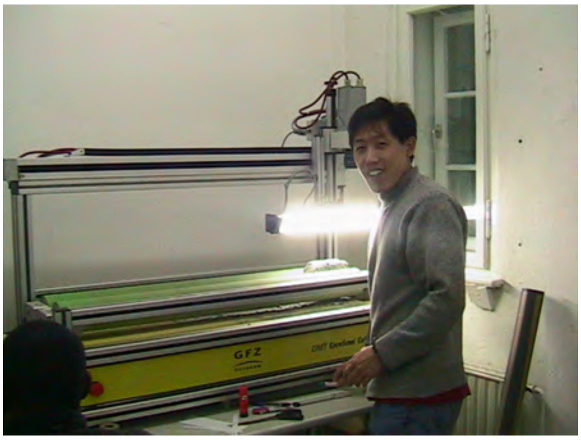


*Fig. 5.10: Optical core scanner in operation*

**Prerequisites for scanning**

Optical scans of whole round cores are essential for initial and long-term digital documentation (and distribution) with the ICDP Drilling Information System. Ideally this happens in the field, right after core retrieval. Thereafter, cores are cut and sampled, annotations of characteristics and sampling made, and/or digital geological profile construction, core-log integration or well correlation, re-orientation, tectonic, petrographic and image analyses are performed.

Interested scientists should apply to use one of the ICDP scanners in their full proposal to ICDP. Requests to use one of the devices are to be made to OSG as early as a drilling timeline is fixed (first-come first-serve policy), but ICDP cannot guarantee that a scanner will be available. The equipment will be provided free of costs on the base of a lending agreement but shipping and related fees are to be covered by the project. If not part of an ICDP grant a maintenance fee may be necessary.

A core scanner at a drill site requires about 2.5 × 2 $m^2$ space in a dry place such as a laboratory trailer, container or similar. Trailer space can be shared with other instruments (e.g., MSCL). Power supply (220V) must be buffered or electrically independent from rig power (e.g., external generator or public power supply).

OSG cannot provide the manpower to operate and maintain the experiment during drilling, but will support it remotely as necessary. Hence, an operating scientist or program-aid (student; temporary technician hired for the project, or project volunteers) has to run the tool. On-site operator(s) of a scanner can be trained by OSG at the GFZ in Potsdam. Costs for specific instrument training are to be shared between the project and ICDP. The on-site operator with OSG support will assemble the experiment immediately before spud in.

**OnLine GAs monitoring OLGA**

Continuous mud gas logging during drilling as well as offline mud gas sampling are standard techniques in oil and gas exploration, where they are used to measure hydrocarbons in reservoir rocks while drilling. ICDP's online gas monitoring OLGA extends this technique for scientific drilling in hydrocarbon and non-hydrocarbon formations to sample and study the composition of crustal gases. Hydrocarbons, helium, radon and with limitations carbon dioxide and hydrogen are the most suitable gases for the detection of fluid-bearing horizons, shear zones, open fractures, sections of enhanced permeability or permafrost methane hydrate occurrences. Offsite isotope studies on mud gas samples serve to reveal the origin and evolution of deep-seated crustal fluids.

OLGA has been proven to be a reliable and inexpensive source of information on the composition and spatial distribution of gases at depth in real time. It is suitable to detect fluid-bearing horizons, shear zones, open fractures, sections of enhanced permeability and methane hydrate occurrences in the subsurface of fault zones, volcanoes and geothermal areas, permafrost regions, and other rheological formations. Offsite isotope studies on mud gas samples help reveal the origin, evolution, and migration mechanisms of deep-seated fluids. It also has important applications to aiding decisions if and at what depth rock or fluid samples should be taken or formation testing should be performed. The method had been successfully applied on several continental scientific drilling projects of ICDP (Mallik, SAFOD, Unzen Volcano, Koyna, COSC-1) and IODP (NanTroSEIZE EXP. 319, 338, 348).

**Operation Flow**

Drilling mud gas that circulates in the borehole comprises air and gaseous components that are mechanically released by the drill bit, including components present in the pore space of the crushed rock and gas entering the borehole through permeable strata, either as free gas or, more likely, dissolved in liquids. Continuous inflow of fluids in the borehole along the entire borehole wall is mostly hampered through the rapid formation of mud-cake that covers the borehole wall and acts as a seal.

Back at the surface, a portion of the circulating mud is admitted to a mud gas separator and gas dissolved in the drilling mud is extracted mechanically under a slight vacuum. The separator is composed of a steel cylinder with an explosion-proof electrical motor on top that drives a stirring impeller mounted inside the cylinder. The gas separator is normally installed in the 'possum belly' above the shaker screens as close as possible to the outlet of the mudflow line to minimize air contamination and degassing of the drill mud immediately before gas extraction (Fig.

8.3). A small membrane pump is used to build up vacuum and to pump the extracted gas into a laboratory trailer, which should be installed not more than a few tens of meters away from the gas separator.

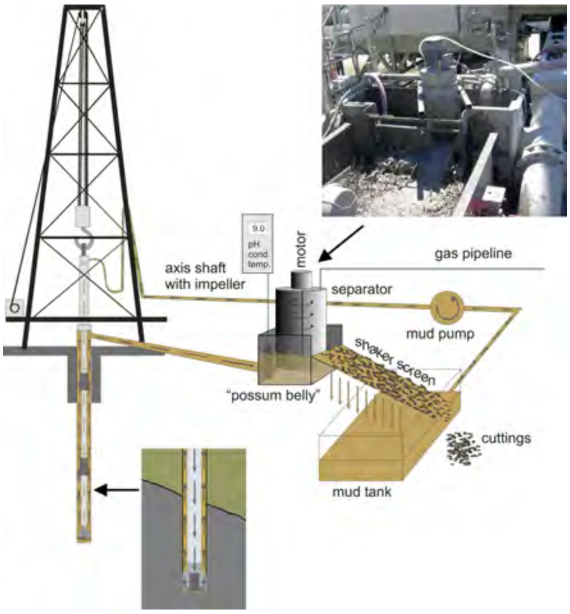


*Fig. 5.11: Scheme of drill mud flow and gas extraction by gas separator; inset photo shows gas separation device*

$N_2$, $O_2$, Ar, $CO_2$, $CH_4$, He, and $H_2$ are determined by a quadrupole mass spectrometer (QMS) of the type OmniStar™ (Pfeiffer Vacuum, Germany). A complete QMS analysis with detection limits between 1 and 20 ppmv (parts per million by volume) is achieved with this setup after an integration time of less than 20s (Fig. 8.4.). However, a sampling interval of one minute is mostly chosen to reduce the amount of data produced. Hydrocarbons ($CH_4$, $C_2H_6$, $C_3H_8$, i-$C_4H_{10}$, and n-$C_4H_{10}$) are analysed at 10-min intervals with an automated standard field gas chromatograph (GC), which is equipped with a flame ionization detector. Detection limits for the hydrocarbons are at about 1 ppmv. Gas samples for further studies e.g., of isotopes are taken automatically when a given threshold level at the QMS is exceeded.

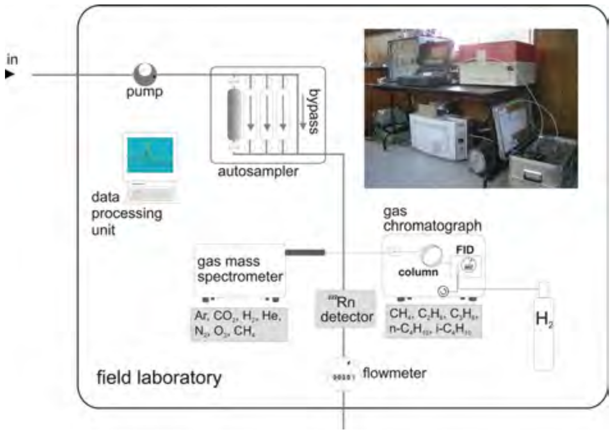


*Fig. 5.12: Flow path of gas analyses steps*

**Prerequisites for gas monitoring**

The drilling mud acts as carrier for fluids and gas transport to the surface. Drilling mud circulation is therefore crucial to apply OLGA. The method is, for example, not applicable for lake drilling. OLGA will not replace commercial mud logging for hazard warning purposes.

ICDP will provide all necessary equipment for a successful execution of the experiment. In turn, the project must provide space ($2 \times 3$ m$^2$) in a laboratory trailer, container or similar facility. Trailer space can be shared with other groups if no liquids (water) are used in the trailer. The lab trailer should be placed in close vicinity (not more than 50 m) to the shale shakers to keep the travel time of the gas short. Power supply (220 V) for the analytical devices in the lab trailer must be electrically separated from rig power (e.g., external generator or public power supply). The power input of the analytical devices is ~1000 VA.

Gas composition data are recorded versus time. Additional data are needed to convert the raw data set into gas composition at depth. These data (lag depth, ROP) must be provided, for example, from mud logging or the drilling company on a minute base (ideally), but at least every five minutes. The equipment will be provided on the base of a lending agreement. Shipping costs, custom fees, etc., are to be covered by the project.

The OSG will offer the OLGA system upon request if a project scientist can run the instrument on the drill site. ICDP will not provide the manpower to operate and maintain the experiment during drilling, but will provide technical support from outside if necessary. In addition, OSG will train the on-site operator(s) before a drilling project starts. The costs for this training will be partly covered by ICDP. The on-site operator and the OSG gas geochemist will assemble the experiment immediately before spud in. OSG offers OLGA as part of a scientific cooperation for joint data evaluation and interpretation. Additional lab investigations on, for example, noble gas isotopes can be arranged by OSG if prepared beforehand.

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# G1 Glossary

**ALPHABETICAL LIST OF ABBREVIATIONS AND THEIR MEANING**

| | |
|---|---|
| ALN | Alien bit coring |
| AOG | Assembly of Governors, ICDP |
| APC | Advanced Hydraulic Piston Corer |
| API | American Petroleum Institute |
| ATP | Adenosine Triphosphate |
| BCR | Bremen Core Repository, Germany |
| BGR | Bundesanstalt für Geowissenschaften und Rohstoffe (Federal Institute for Geosciences and Natural Resources), Germany |
| BHA | Bottom Hole Assembly |
| BHTV | BoreHole TeleViewer |
| blf | Below lake floor |
| BOP | Blowout-preventer |
| BO | borehole breakout |
| CC | Core Catcher |
| CC licenses | Creative Commons, non-profit organization released several copyright-licenses known as Creative Commons licenses |
| CCS | Carbon Capture and Storage |
| CCSF | Core composite depth below seafloor |
| CCT | Composite Coil Tubing |
| CNS | Carbon-Nitrogen-Sulfur |
| Corelyzer | Open access, free application for visualization and annotation of scanned core sequences and log data |
| COSC | Scandinavian Caledonides Drilling Project |
| Correlator | Open access, free application for log data splicing, composing and matching |
| CSF-A bzw. B | Core depth below seafloor |
| CSDCO | Continental Scientific Drilling Coordination Office, U.S.A. |
| CLSI | core-log-seismic integration |
| CT | Coiled Tubing |
| CCT | Composite Coil Tubing |
| CurationDIS | Drilling Information System for a specific storage place for sample material |
| CV | Curriculum Vitae |
| DAS | optical geophone arrays |
| DCO | Deep Carbon Observatory |
| DFDP | Deep Fault Drilling Project, New Zealand |
| DFG | German Research Foundation |
| DGLab | Deep Geodynamic Laboratory-Gulf of Corinth |
| DIS | Drilling Information System, tool for data acquisition of scientific drilling projects |
| DITF | Drilling Induced Tensile Fractures |
| DLDS | Deep Lake Drilling System |
| DLIS | Digital Log Information Standard |
| DMT | Deutsche Montan Technologie, Exploration Company |
| DMP | Data Management Plan |
| DNA | Deoxyribonucleic Acid |
| DSF | Drilling depth below surface |
| DRF | Drillers depth below rig floor |
| DTS | distributed temperature sensing |
| DSS | distributed strain sensing |
| DAS/DVS | distributed acoustic or vibration sensing |
| DOI | Digital Object Identifier for publications, data sets |
| DOSECC | Drilling, Observation and Sampling of the Earth's Continental Crust's |
| DTS | Distributed Temperature Sensing |
| DWOP | Drilling Well On Paper |
| DEVI | deviation from vertical |

| | |
|---|---|
| EC | Executive Committee, ICDP |
| ECD | Equivalent Circulating Density |
| EOS | Transactions, American Geophysical Union, Earth & Space Science News |
| EPOS-ERIC | European Plate Observing System Data Infrastructure |
| EXN | Extended shoe, non-rotating |
| Expedition | Time period of drilling operations and lab work |
| ExpeditionDIS | Drilling Information System for a specific Expedition |
| FAR-DEEP | Fennoscandia Arctic Russia - Drilling Early Earth Project |
| FBG | Fiber Bragg gratings |
| FPI | Fabry-Perot interferometer |
| FO | Fibre-Optic |
| GC | Gas Chromatograph |
| GCR | Gulf Coast Repository, TAMU, Texas, U.S.A. |
| GDEM | Advanced Spaceborne Thermal Emission and Reflection Radiometer#ASTER Global Digital Elevation Model |
| Geotek | Geotek (www.geotek.co.uk/) |
| GESEP | German Scientific Earth Probing Consortium e.V. |
| GFZ | German Research Centre for Geosciences, Helmholtz Centre Potsdam |
| GLAD | Global Lake Drilling unit |
| GMS | Gas Membrane Sensor |
| GNU | General Public License for software |
| GONAF | Geophysical Observatory at the North Anatolian Fault |
| GR | Gamma radiation |
| GRAPE | Gamma Ray Attenuation Porosity Evaluator |
| HPC | Hydraulic Piston Coring |
| HP/HT | High-Pressure, High-Temperature |
| HQ | diamond coring diameter (core diameter=64 mm) |
| HSE | Health, safety and environment |
| HPC | Hydraulic Piston Corer |
| IGOR | Software |
| ICDP | International Scientific Continental Drilling Program |
| IGSN | International Geo Sample Number, unique IDs for sample material and samples |
| IODP, ODP | International Ocean Discovery Program (since fall 2013), previously Integrated Ocean Drilling Program (2003-2013), Ocean Drilling Program (1985-2003) |
| IPM | Integrated Project Management |
| JRV | Joint Research Venture – funding agreement between ICDP and the Principal Investigators |
| KCC | Kochi Core Center, Japan |
| KTB | Deep Crustal Lab of GFZ |
| LacCore | National Lacustrine Core Facility in Minneapolis, Minnesota, USA |
| L2S | Land-2-Sea |
| LIS | Log Information Standard |
| LIMS | Laboratory Information Management System |
| LWD | Logging While Drilling |
| LWT | logging-while-tripping |
| MAASP | MAximum Allowable Surface Pressure |
| MCD | Meters corrected depth |
| MCPD | Meters composite depth |
| mDIS | Mobile Drilling Information System |
| METI | The Ministry of Economy, Trade, and Industry of Japan |
| MLS | memory logging sondes |
| MoU | Memorandum of Understanding, legal agreement, e.g. between ICDP and ICDP member country |

| | |
|---|---|
| MRI | Magnetic Resonance Imaging |
| MRES | Borehole fluid resistivity |
| MS, MSUS | Magnetic Susceptibility |
| MSCL | Multi-Sensor Core Logger |
| MTBF | Mean-time between failure |
| MWD | Measurements While Drilling |
| NASA | National Aeronautics and Space Administration, U.S.A. |
| NanTroSEIZE | Nankai Trough Drilling Program of IODP |
| NMR | Nuclear Magnetic Resonance |
| NSF | U.S. National Science Foundation, U.S.A. |
| NQ | diamond coring diameter (core diameter=48 mm) |
| OBS | Ocean bottom seismometer |
| Off-site | Laboratory or storage place away from the drill site (= on-shore) |
| OLGA | On-Line Gas monitoring of circulating drilling mud |
| On-site | Nearby the drill rig, on land or on water (= off-shore) |
| OSG | Operational Support Group, a team of scientists, engineers and technicians hosted at GFZ to assist in planning, management and execution of ICDP projects |
| OTDR | optical time domain reflectometry |
| PANGAEA | Data Publisher for Earth & Environmental Science |
| PDM | Permanent Downhole Monitoring |
| PH | Pilot -hole |
| PhD | Philosophiae Doctor |
| PI, Co-PI | Principal Investigator, Cooperating Principal Investigator |
| PMBOK | Projekt Management Body of Management |
| PQ | diamond coring diameter (core diameter=85 mm) |
| PSE | Personal Safety Equipment |
| PU | Polyurethane |
| PVC | Polyvinyl Chloride |
| PWA | Progressive Web App |
| QC | Quality Control |
| QMS | quadrupole mass spectrometer |
| QR-code | Quick Response - matrix barcode (or two-dimensional barcode) |
| RGB | Red-Green-Blue color scheme |
| RLF | Reduced Label Format |
| ROP | Rate of Penetration, depth progress |
| RW | Resistivity of Water |
| SAFOD | San Andreas Fault Zone Observatory at Depth |
| SAG | Science Advisory Group, ICDP |
| Sample | Any sample material (incl. fluids, gas) out of a hole, including the hole virtually Material |
| Samples | Parts and pieces taken from the stock of sample material for further investigations |
| SCOPSCO | Scientific Collaboration on Past Speciation Conditions in Lake Ohrid |
| SD | Scientific Drilling journal |
| SGR | Spectral Gamma Ray |
| SM | Social Media |
| SMP | Sample management plans |
| SP | Self Potential |
| SRTM | Shuttle radar topography mission, NASA |
| Spud-in | Beginning of a drilling, when the drill bit touches the ground for the first time |
| STM | Science Team member |
| TAMU | Texas A&M University |
| TC | Total Carbon (inorganic and organic carbon content) |
| TCDP | Taiwan Chelungpu-fault Drilling Project |
| TFA | Total flow area |

| | |
|---|---|
| TIC | Total Inorganic Carbon |
| TOC | Total Organic Carbon |
| TQ | Torque |
| TV | Television |
| TVD | True Vertical Depth |
| UWITEC | Coring tool manufacturer |
| VAT | Value Added Tax |
| VueJS | Javascript Framework |
| VCD | Visual Core Description |
| VSP | Vertical seismic profiling |
| WDS | Wavelength Dispersive X-ray Spectrometry |
| WellCAD | Commercial tool for log data processing and visualization |
| WOB | Weight On Bit |
| XCB | Extended Core Bit, rotating |
| XDIS | eXtended Drilling Information System |
| XRD | X-Ray Diffraction analysis to determine minerals and mineral content of a sample |
| XRF | X-Ray Fluorescence |
| XTN | Extended Noose coring |

# G2 DOWNHOLE LOGGING GLOSSARY

## ALPHABETICAL LIST OF LOGGING RELATED TERMS WITH EXPLANATIONS

ACCEL
Acceleration, a log parameter, measured typically by an axial accelerometer sensor to survey a sonde's motion, to show that the sonde is moving and is not stuck or stopped.

Active Sondes
Sondes that excite the formation either by emitting various kinds of signals (acoustic, electric, magnetic, radiation, nuclear particles) or by applying mechanic or hydraulic forces to the formation. Therefore, such sondes comprise a transmitter and a receiver as opposed to passive sondes, having only receiving sensors and measuring naturally occurring signals.

Borehole Effects
see Environmental Corrections

Bit Size (BS)
The outer diameter of the drill bit. Beware: To describe a hole size do not use the core size (= inner diameter of the bit)! Use only the bit size to describe the hole size in discussions between loggers and drillers. This is because a certain core size can be gained by very different sizes and types of drill bits.

Cable, Logging
A logging cable typically consists of a strand of several electric conductors (copper lines) surrounded by two layers of high-strength steel wire. Typical are mono, 4-conductor, and 7-conductor cables. Less common are cables where one or more copper lines are replaced by fiber-optic lines. The logging cable is stored on and lowered into the hole by a specific logging winch.

Cable Head
The cable head is the downhole-side termination of a logging cable and is firmly attached to the cable. It contains the electric connectors and an easy screw-on mechanical connection to the sonde head for a quick connect/disconnect of cable and sonde even at rough field working conditions.

Calibration, Sonde
Logging sondes, as most scientific instruments, do not measure the desired parameter directly but measure a voltage or a current. These readings are transformed to the desired parameters by calibration of the sonde, usually in a shallow borehole of very well know physical properties (calibration pit) but it also can be done in a calibration device of laboratory scale.

Caliper
The diameter of the borehole cross section. A borehole cross section usually is not circular but irregular due to wall collapses, washouts, formation creeping into the hole etc. A standard caliper sonde has four arms opening radially towards the wall and reading their opening width.

Cased Hole Logging
is in general any borehole measurement carried out inside a casing or a pipe that is installed in a hole. Specifically, there is a number of logging tools designed to perform inside steel casings.

Centralizer/Eccentralizer
A device mounted to or being part of a logging sonde that keeps the sonde body as best as possible in the center of a borehole. An eccentralizer does the opposite and pushes the sonde against the

borehole wall. Centralizers usually consist of several bow springs arranged cage like around the sonde. An eccentralizer can be a powered arm or a single bow spring.

Curve, Logging
The depth-related data set of a logging parameter of equidistant spacing. A curve consists of two columns of which depth is the first one (reference) and the parameter the second. A logging parameter may also be recorded vs. time, e.g., during stationary measurements.

Cuttings
Chips of rock generated while drilling when the drill bit either crushes brittle rock or cuts soft formations. A diamond coring bit does not produce cuttings but instead rock flour. Cuttings are brought to surface by the mud circulation and are separated from the mud at the shale shakers. The analysis of cuttings allows to determine the mineralogy, size, shape, color and texture.

DAS
see FO Cable

Data Acquisition System
The surface-based electronic and nowadays typically digital counterpart of the downhole sonde. Besides the data acquisition it also powers and controls the sonde functions. It is commonly operated by a specific software on a connected computer.

DAZI
Drift azimuth: azimuth of the drift, which is the deviation of the hole axis from vertical, see HAZI

Depth
In boreholes the parameter depth always is the distance between the well head and a point in the borehole path. In holes with almost no deviation from vertical the depth is equal to the true depth below surface. In deviated holes the borehole depth can be very different (always larger) from the true depth below surface, see also TVD.

Depth Increment
The constant spacing between two data points of a logging curve. Typical values are 10 cm, 0.5 foot = 15.24 cm, and much smaller values with borehole imagers of a few millimeters.

Depth Matching
also, depth correlation. As any depth measurement in a borehole is not error-free, each measurement (logs and also driller depth-derived as of cores and cuttings) initially will be more or less depth-off-set to the other measurements. Unfavorably in most cases this is not obvious when plotting the curves side-by-side. Therefore, it is crucial that each borehole measurement is depth matched to the other measurements. Commonly this is achieved by correlating the parallel recorded natural total gamma ray curves (GR) from each of two independent measurements (logs and cores/cuttings data) but also the magnetic susceptibility (MSUS) is very suitable for depth matching.

Depth of Investigation
see Radius of Investigation

Depth Reference (Zero)
Fixed reference point close to or at the well head where the logger depth is set to zero (0 m) when the sonde reference point, typically either bottom of the sonde or the cable head, is at this position before the sonde is run downhole. Afterwards on return to surface this checked for depth measurement reliability.

Depth System
A device mounted right in front of a wireline logging winch drum to measure the unspooling (running into the hole) and winding up (running out) of the logging cable. Basically, it consists of a measuring wheel (depth wheel) that is pressed against the cable.

DEVI
Borehole deviation from vertical, a log parameter, commonly with values varying

from 0° (vertical) to 90° (horizontal), but upward deviation is also possible, e.g. of boreholes drilled upwards from a mine shaft.

DTS
: see FO Cable

Eccentralizer
: see Centralizer

EFA-LOG
: Electrofacies Log, described in detail in the main text chapter 4.6 Downhole Logging

Enlargement of the borehole
: Any widening of the borehole cross section from the originally circular shape (diameter of the drill bit).

Environmental Corrections
: also called borehole corrections. Borehole effects can distort sonde readings so much that the interpretation of uncorrected data would lead to wrong results. The degree of influence on the downhole logs depends on the type of sonde and on the type of borehole effect: type and condition of the drilling fluid (mud), variations of the hole diameter, drill pipes and casing. Corrections have to be applied to the raw logging data of some sonde types to eliminate as good as possible the distorting.

FS
: Fluid sampler, a sonde to take fluid samples downhole at desired depths. Several types of different methods are available. To gain not only liquid samples but also gas samples the FS has to preserve the in-situ pressure at sampling depth, e.g. a PDS fluid sampler.

FO Cable
: Fiber-optic cable mainly for stationary temperature and pressure measurements (e.g., DTS), for seismic monitoring (DAS) or for monitoring of strain variations. For details see chapter 4.6 on *Permanent Downhole and Fluid Monitoring*

gAPI
: see GR

Geometry, Borehole
: The spatial orientation of the borehole path (trajectory) and the shape of the borehole cross section, where sometimes only the hole shape is referred to as *borehole geometry*. It includes the measured parameters DEVI, HAZI, Depth, Caliper(s) and the derived parameters true vertical depth (TVD), North-South distance (Northing), West-East distance (Easting).

Geophone Chain
: is a chain of several borehole geophone sondes connected by pieces of logging cable. The spacing between the geophones, the so-called inter-tool cable length, is variable.

GR
: Total natural gamma radiation, a log parameter, typically not given as count rate [counts/s], which is strongly dependent on the sonde geometry but calibrated with respect to the sonde reading in a dedicated calibration borehole and given in [gAPI], called *gamma API* units (API: American Petroleum Institute).

HAZI
: Hole azimuth, a log parameter, the geographical direction of the borehole axis (0° to 360°, with North = 0° and East = 90°). Sometimes this parameter is labelled AZIM or DAZI (for drift azimuth). Note: in a hole with only very low deviation from vertical (< 1-2 deg) the azimuth effectively is indeterminate but the sonde still measures and records values, which are not meaningful.

Horner-Plot method
: estimates the original, undisturbed temperature in a borehole that has a temperature profile being disturbed by e.g. the cooling by mud circulation.

Housing, Sonde
: The outer sonde shell containing electronics, sensors, motors and mechanics etc., mostly made of steel and some housing components made of. It has to

withstand high pressure, temperature, mechanical strain and resist corrosive fluids.

Imager, Borehole

Borehole imagers scan the wall surface either acoustically, electrically or optically, always yielding a North-oriented, high-resolution image of the borehole wall and the structures on it. Because the physical methods of these three imager types are different, their images will not always show identical but similar wall features. These images can be compared with cores and core-scans. Acoustic imagers are also called borehole televiewers (BHTV).

iMLS

ICDP memory logging system: an autonomous system of several downhole sondes, surface depth measuring systems for drill pipe deployment, and dedicated software. For the method see Memory sondes

Invaded Zone

In porous formations this is the volume directly surrounding the borehole, which is completely flushed by drilling fluid. Further out this zone is followed by a transition zone with decreasing fluid invasion towards the undisturbed zone.

Log

This term can have different meanings. For one, log simply can be the short form for log curve like in a plot that is the data pair depth-log parameter. The other meaning describes the actual measuring operation in the borehole. The latter is also ambiguous and very often used synonymously with the term Logging Run, see there.

Logging Direction

The measuring direction in the borehole: upwards (standard for most sondes) or downwards (typical e.g., for a log of the temperature and other fluid parameters).

Logging Run

This term confusingly can have different meanings and also is sometimes used synonymously with the term *Log*.

- First, the logging operation with one specific sonde/sonde string beginning with running in till dismounting the sonde from the hole, e.g., run 1 = GR-SGR-MSUS, run 2 = GR-BS-DIP. - Second, it can mean the individual recording of one specific sonde/string over a certain depth interval, e.g., the string GR-SGR-MSUS is run in and logs section 200-500 m (run1), then for quality control the repeat section 200-250 m (run 2), and then the section 30-200 m (run 3).

- Third, the term is used almost synonymously with the term Logging Series, for example *logging run 2* of a borehole would be the second time logs are recorded in this borehole.

- The OSG vocabulary follows the first meaning:

a *Run* is everything between inserting the sonde into the hole and until it gets out again,

a *Log* is a single record over a depth section.

Logging Series/Session/Campaign

A sequence of several usually, but not necessarily, different logging runs typically after drilling has reached a certain depth of the borehole. Logging series are planned in advance as part of the entire drilling and logging plan, in contrast to shorter individual logs with only one or a few sondes, which are inserted at short notice due to acute scientific or drilling requirements.

LWD - Logging While Drilling

A method of downhole logging where autonomously powered and measuring sondes are firmly incorporated into the drill string. They are positioned a few meters above the drill bit and measure literally while drilling, which means they deliver logging data almost immediately after the borehole is created. The range of available tool types is comparable with wireline tools.

LWT - Logging While Tripping
A method of downhole logging where autonomously powered and measuring sondes (memory sondes, no logging cable required) are positioned at the bit soon after drilling of a hole section has finished. They measure while they are pulled to surface with the drill string (trip-out). This method allows logging in strongly deviated holes and even in collapsing hole sections, where wireline logging is impossible. It also allows to cool the sondes by mud circulation during logging.

Main Log
One log out of a sequence of logs with the same sonde during one logging run, chosen by the logging engineer to be the representative log for the respective logging interval. The other logs from this logging run are so-called repeat logs. Repeat logs are usually performed to verify the sonde repeatability. They typically cover some tens of meters of the logging interval, which means in short boreholes the repeat section can cover the entire logging interval.

Memory sondes
Autonomous slimhole logging sondes with internal power supply, performance of the measurements and data storage. They are run without logging cable, usually at the bottom of a coring drill string in logging while tripping mode (see LWT).

MNEM
Mnemonics, short labels of either the different sonde types (e.g., SGR = spectrum gamma ray sonde, BCS = borehole compensated sonic sonde) or the measured and derived curves from these sondes, e.g., VP = p-wave velocity or RDEEP = resistivity of the DLL sonde, reading deep into the formation.
Beware: sometimes mnemonics of sonde and log curve are identical, e.g. MSUS, GR or TEMP can be sonde names or as well be curve names.

Mud or Drilling Mud
Denominates the liquid inside a borehole, regardless of its composition (oil-based, water-based, with/without solids, additives as chemicals, clays, barite, peat, etc.). Mud is required for multiple purposes regarding drilling of the hole. In the context of downhole logging the knowledge of the mud properties is important as they can affect the measurements, see also Environmental Corrections or even forbid some logging sondes.

Mud Cake
Hydraulic pressure in the borehole higher than formation fluid pressure can cause invasion of permeable zones with the mud and it's solid constituents. The permeable formation acts like a filter accumulating the solids close to and ultimately also on the hole wall building up a sometimes several centimeter thick cladding on the wall within a permeable zone, thereby strongly reducing its effective permeability. Furthermore, the resulting reduction of the hole size can potentially prevent wireline sondes from passing through these zones.

MP log
Mud parameter log, comprises several parameters as temperature, pressure, fluid resistivity, pH, etc.

MSP
moving/multiple source seismic profiling, see VSP

MSUS
Magnetic susceptibility, a log parameter.

Nuclear Sondes
Sondes that contain a radioactive source, which emits gamma rays or neutrons. The source can be chemical (typically $^{137}Cs$ for gamma rays, $^{241}AmBe$ for neutrons) or an accelerator for neutrons.

Observation Scale
: The size of the volume a measurement investigates, typically described by its diameter or edge length. In the various borehole related investigations these range from very small scale (thin sections, cuttings) then cores, overlapping with downhole logging, again overlapping with borehole seismics to surface seismics on the very large scale end. See also the text.

Open Hole Logging
: see Cased Hole Logging

Orientation of the borehole
: see Geometry, Borehole, DEVI, HAZI, Trajectory

PDS
: is a type of fluid sampler, see FS

Probe, Logging
: see Sonde

Radius of Investigation
: The radius of the volume around the sonde sensor(s) from which 90% of the signal stem from. Each sonde type has a range of radii depending on borehole conditions, including the measured formation itself. For example, a highly resistive formation will cause a very large radius and reversely a low resistivity formation will cause a small radius of investigation.

Relative Bearing (RB)
: Angle between a certain marker on a sonde, e.g., one caliper arm, and the high side of the sonde, the latter being determined gravitationally.

Repeat Log
: see Main Log

Rig Time
: In context of downhole logging this is the time during logging operations when the drill rig and maybe also the drill crew is on stand-by and does not drill but yet causes hourly costs. In a logging plan these rig costs have to be considered additionally to the costs of the logging service provider.

Sampler, Downhole
: a general term for borehole sondes that take samples of fluids or cuttings or drill side cores.

SEGY
: Seismic data format

SGR
: spectrum gamma ray, name of a sonde and also of the log, delivering contents of U, Th, K

Sheave
: A grooved wheel to guide the logging cable on its way from the logging winch to the well mouth. It has a groove fitting the specific logging cable size. At least one but usually two sheaves are installed on the drill rig, a tripod or a crane above the borehole.

Sonde (Logging)
: In the context of downhole logging the term *logging/downhole sonde* (or *tool* or *probe*) is the general term for any instrument measuring or taking samples inside a borehole.

Sonde String
: A mechanically firmly connected combination of several logging sondes, where the individual sondes are screwed together over each other, as opposed to e.g., a geophone chain with flexible connections.

Sonic
: may describe the sonde and the log curve(s)

Sonic Picking
: is a typical processing of sonic waveforms, where the first arrival times of p-, s- and maybe Stoneley-waves are identified and recorded (picked) in order to calculate the respective velocities.

Speed, Logging
: is the velocity of the sonde moving up or down while measuring. Each sonde type has a specific maximum logging speed, which must not be exceeded. The sonde

may be run in or out much faster when not measuring.

Stationary Measurements
: A time-based recording where the sonde is kept at one depth in the hole, primary to observe temporal changes. Best-known is the stationary temperature log at bottom of the logging interval to estimate the undisturbed formation temperature.

Stoneley wave
: A sonic surface wave that propagates along the borehole wall/fluid interface. It is used to localize zones with fractures or other high permeability.

Structure Picking
: is a typical processing of borehole imager data. It allows to identify and record the sine-wave shaped intersection line of planar structures with the cylindrical borehole wall and also the position and size of borehole breakouts and of subvertical drilling induced fractures (see in the text).

Telemetry, Sonde
: A downhole sonde component necessary to provide communication and data transfer from sonde to surface and vice versa. Modern sondes use digital data transmission and communication, only few sondes still have an analog telemetry. Telemetry sondes might also include sensors, e.g., for GR, acceleration, inclination, temperature.

Televiewer
: see Imager. Borehole televiewer (BHTV) is an earlier name for an acoustic imager.

Tension, Cable
: is the force (in [N] or equivalent in [kg]) with which the winch is pulling on the logging cable.

Tool, Logging
: see Sonde

Trajectory, Borehole
: is the more or less winding path of the borehole from the well head to the bottom of the hole. It is derived from borehole orientation measurements, see Geometry, Borehole.

TVD
: True vertical depth. The depth of a point on the borehole path vertically below surface, gained from borehole orientation measurements.

Vertical Resolution
: The sonde-specific shortest vertically resolvable thickness of a unit in a borehole. It mainly results from the sensor size and the measuring geometry, like the spacing between a source and a receiver.

Volume of Investigation
: This is the volume of formation around or in front of a sonde from which approximately 90 % of the measured signal come from. It is determined by the vertical resolution and the radius of investigation. Not only the size but also the shape of this volume is very sonde-specific.

VSP - Vertical Seismic Profiling
: A seismic borehole measurement along the borehole axis. During a VSP commonly a chain of several borehole geophones is positioned stepwise along the borehole while a seismic source at surface generates seismic signals. The recordings of the direct wave from surface to the receivers yields a high resolution seismic velocity profile along the borehole path. Typically, the surface seismic source is a method that easily allows for very high repetition rate of shots, vibrators on land and air guns in offshore applications but also explosive sources get used. For simplicity the method is called VSP even if a part of the borehole path is not vertical. While the above described procedure can also be named Zero Offset VSP (source at the well head), a VSP might also have another source away from the well head, called Offset VSP. If the surface source is positioned in certain patterns around the well head this is called Moving/Multiple source Seismic Profiling -

MSP or Walk-Away VSP, delivering multiple high resolution seismic sections.

Washout

A large, omnidirectional, and approx. uniform enlargement of the borehole. The name derives from sediment drill holes where in zones of soft formations the drilling mud circulation alone can erode the borehole wall and literally wash away the soft formation.

Wireline

in context of downhole logging another name for the logging cable.

Winch, Logging

A special winch for wireline logging with an electric slip-ring cable outlet in the cable drum axle that allows permanent electric connection with the downhole sonde while the drum is rotating.

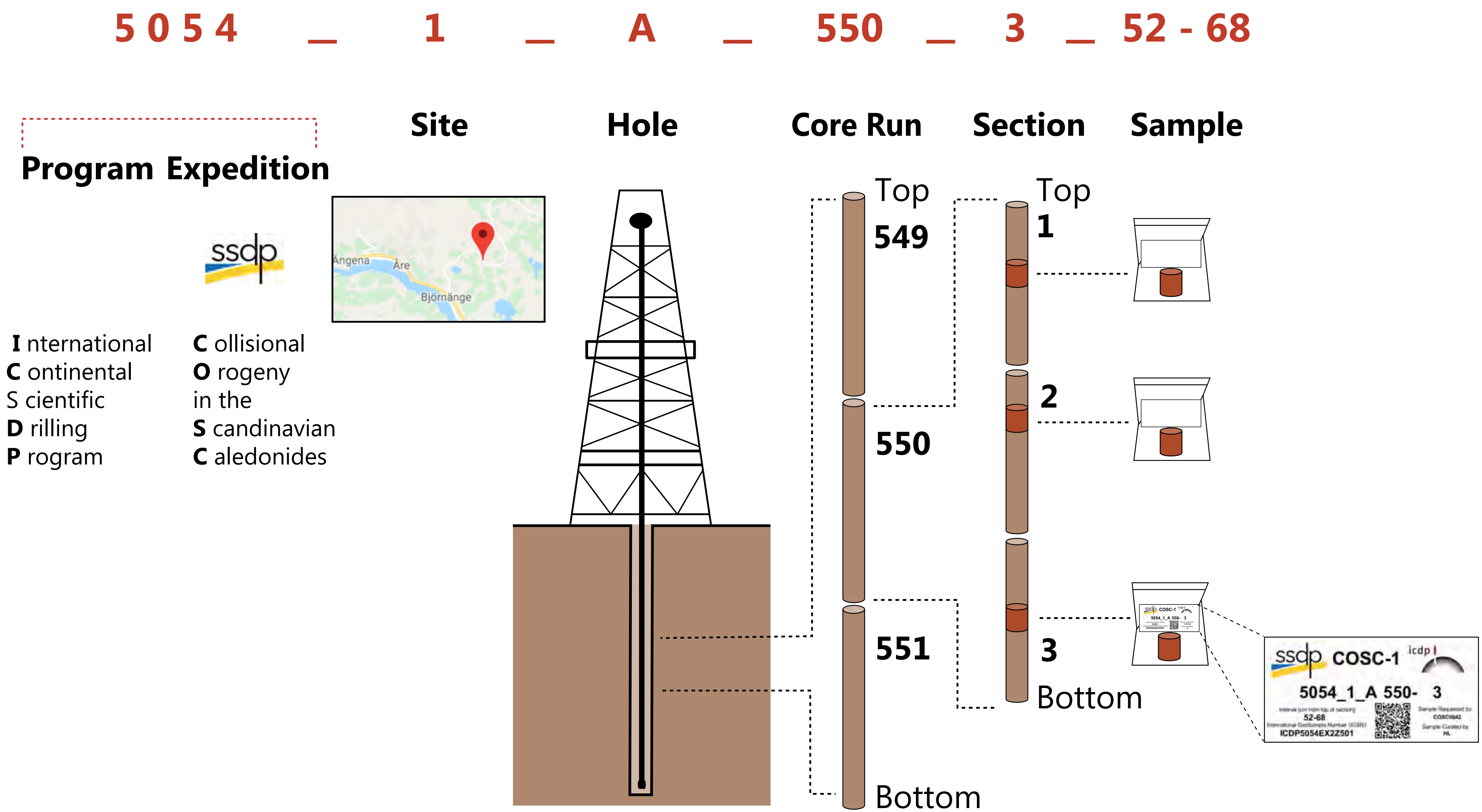
Zero-Offset VSP

see VSP

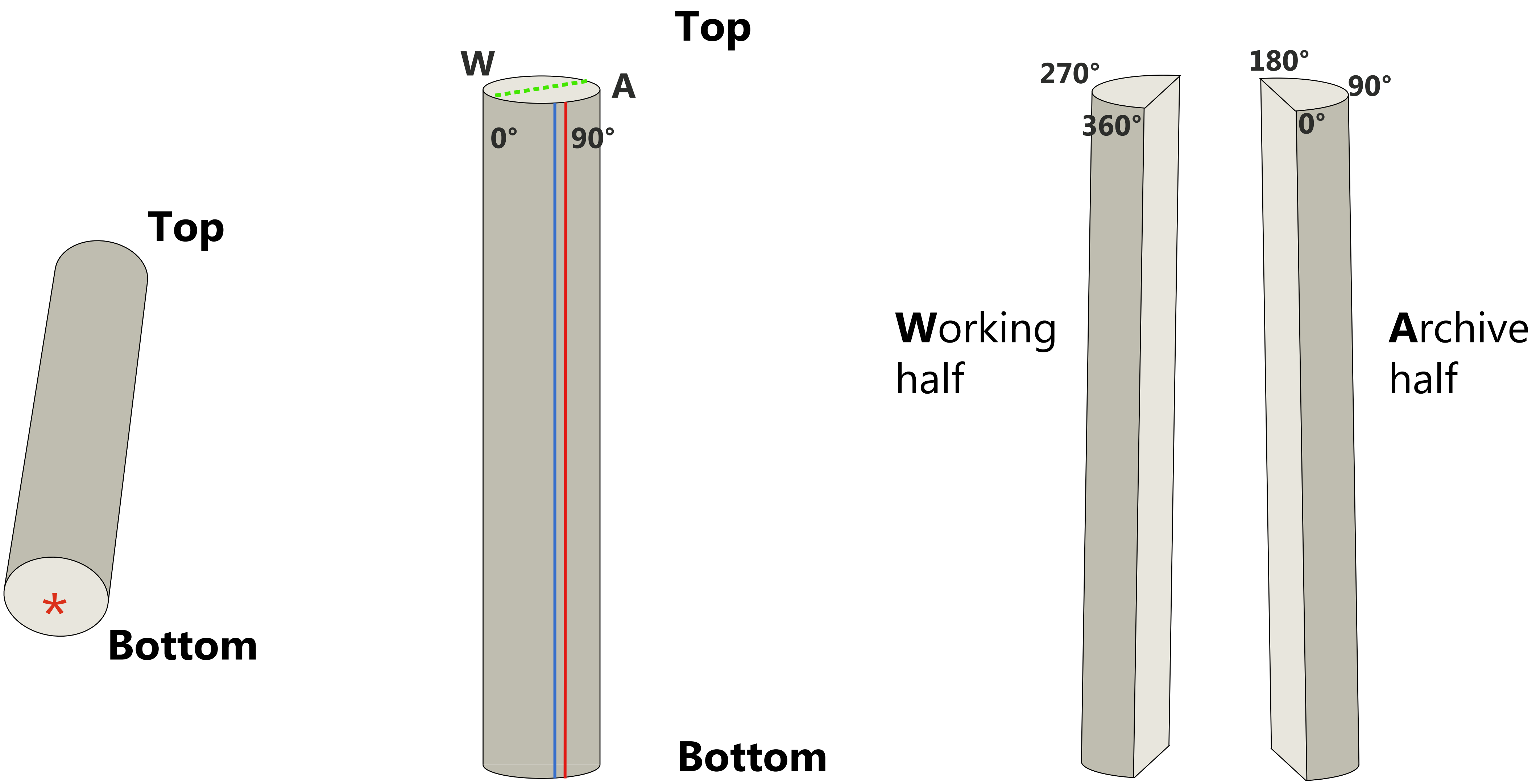
| **Project:** | **PIs:** |
|---|---|
| | |

| | No | TASK | Yes | No | Tbd | $ | Actions |
|---|---|---|---|---|---|---|---|
| **Pre- Drilling** | 1 | Submit Pre-Proposal | | | | | |
| | 2 | Submit Workshop-Proposal | | | | | |
| | 3 | Call for Workshop<br>- Announcement<br>- Publication | | | | | |
| | 4 | Organize the Workshop<br>- Date & Time<br>- Venue<br>- Agenda<br>- Participants<br>- Accommodation<br>- Cost control<br>- Workshop report | | | | | |
| | 5 | Submit Full-Proposal<br>- Personnel and Responsibilities<br>- Budget<br>- Tools<br>- Training / Consulting<br>- Workflow<br>- Lab(s) and Repository | | | | | |
| | 6 | Determine policies and collect agreements for<br>- Moratorium Period<br>- Science Team & responsibilities<br>- Data & sample sharing<br>- Publication guidelines (incl. Citation) | | | | | |
| | 7 | Organize data acquisition and data storage<br>- Workflow<br>- Data & sample curator(s)<br>- Shifts & Personnel Plan<br>- Hardware / Software<br>- Local Infrastructure & Network<br>- define Basic Data Sets | | | | | |

# Core Handling: Naming Convention

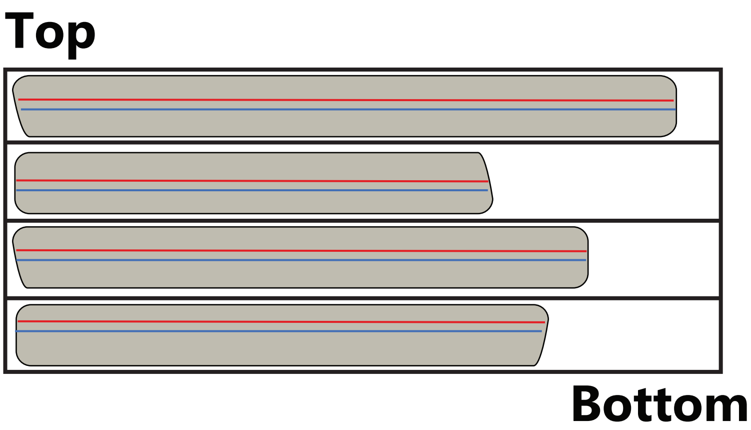


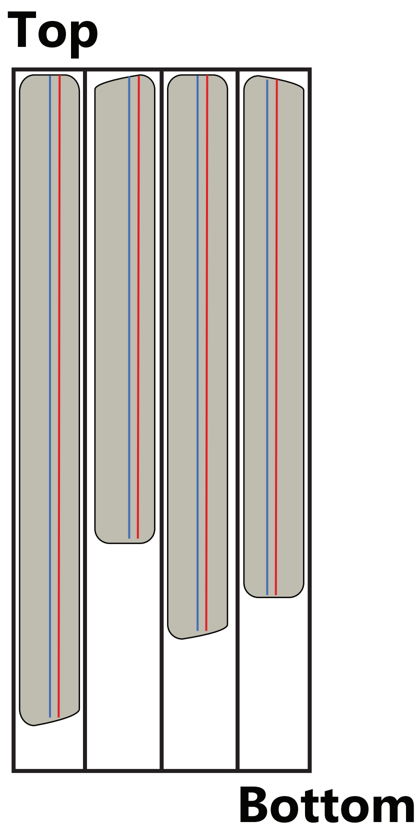
# Core Marking

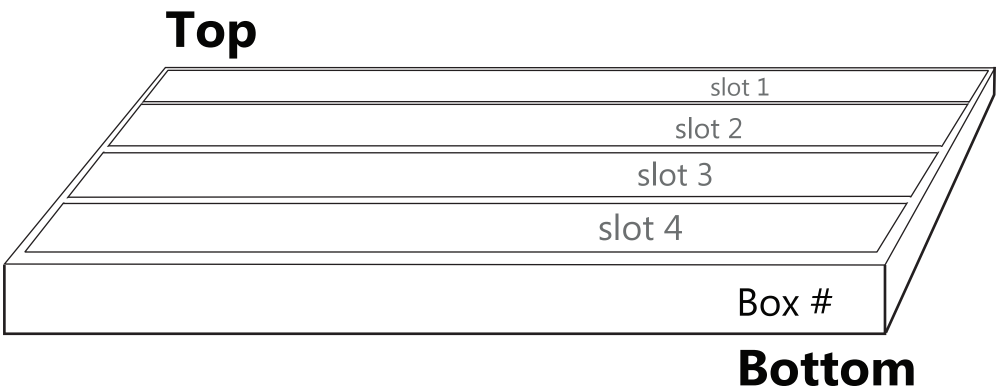


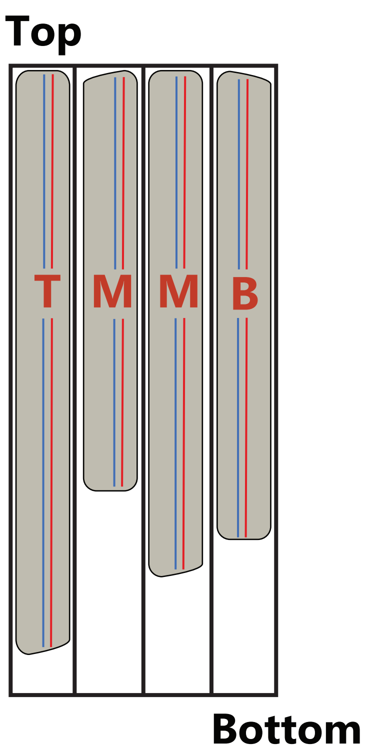

**“Red on the Right side”**

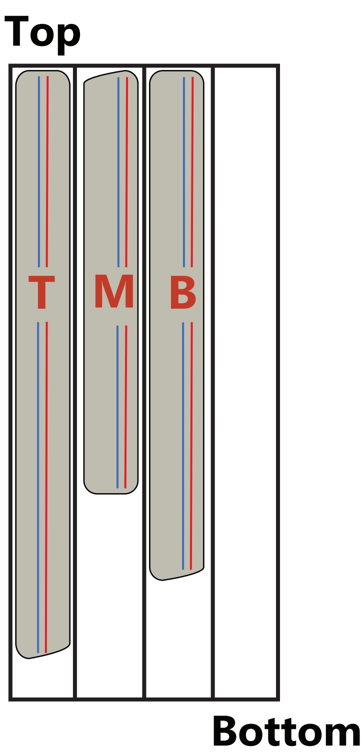
# Core Box Handling

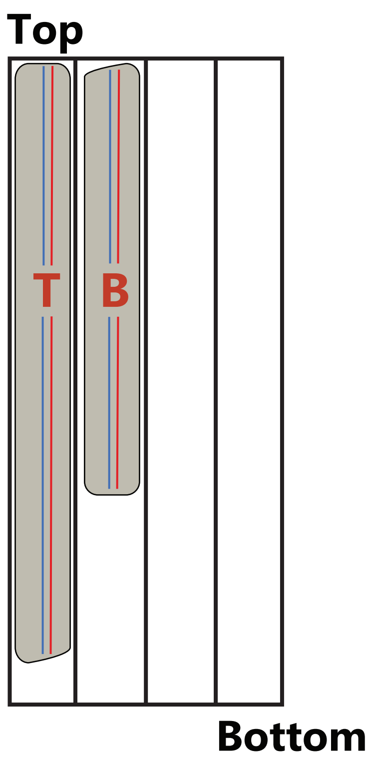


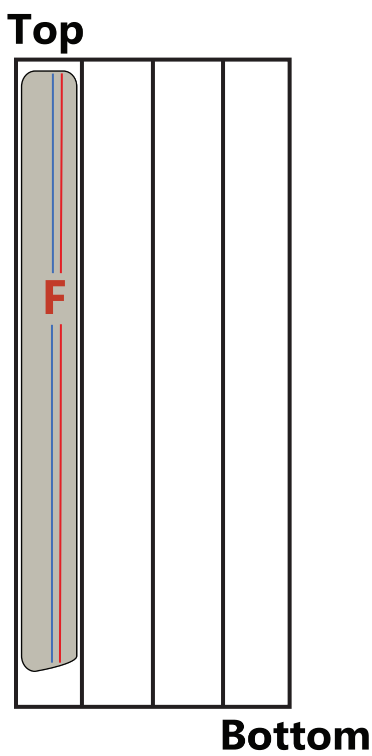



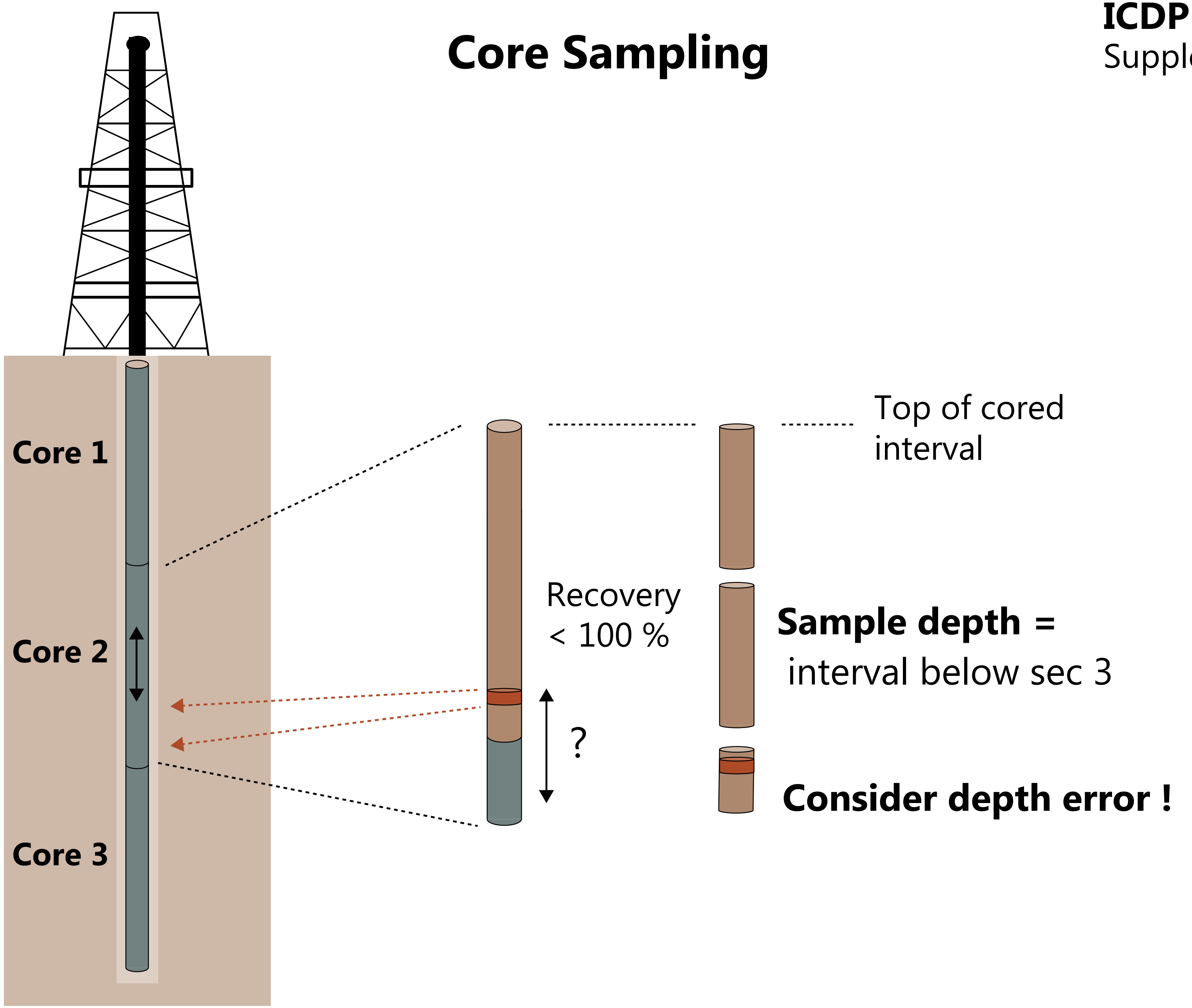



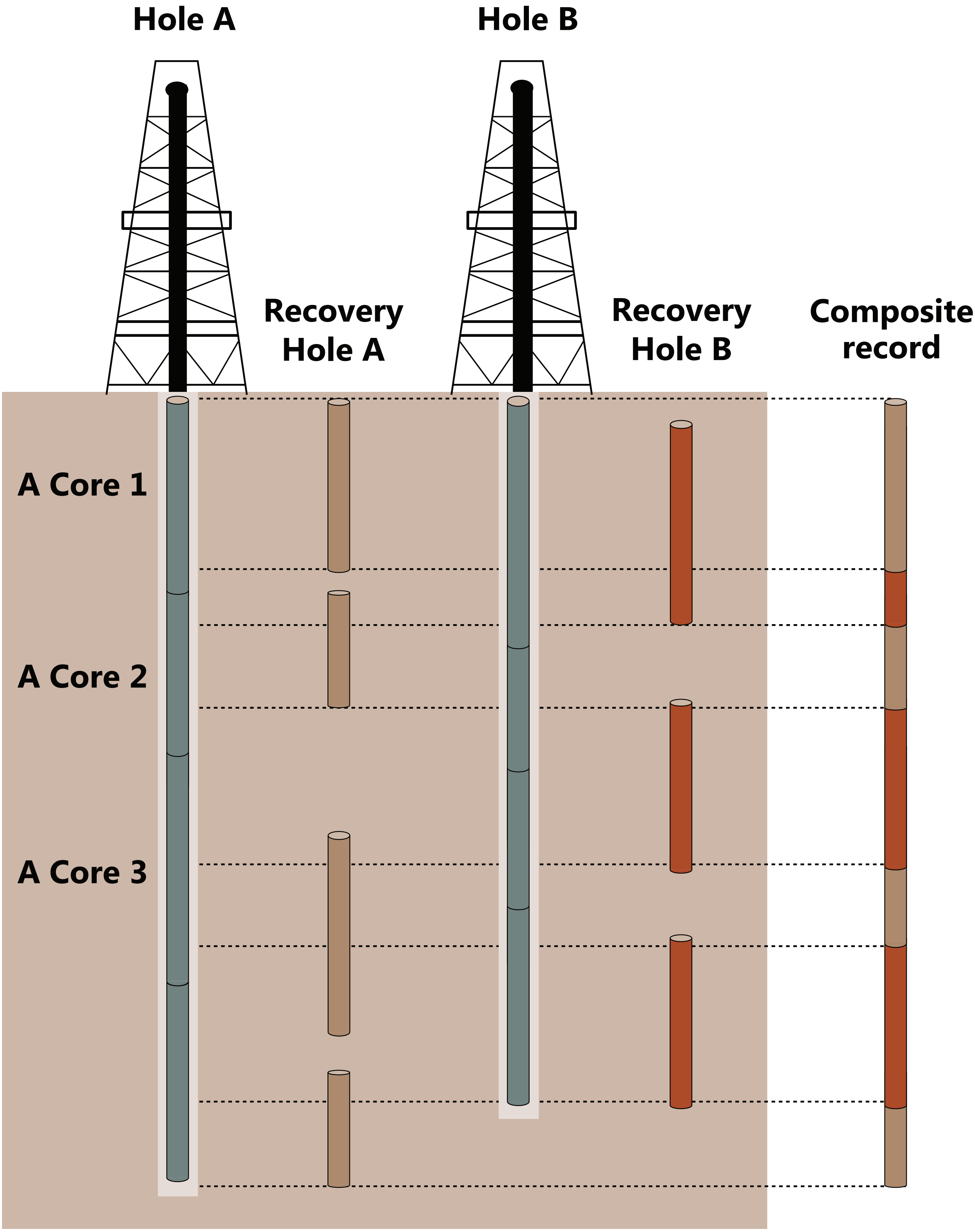



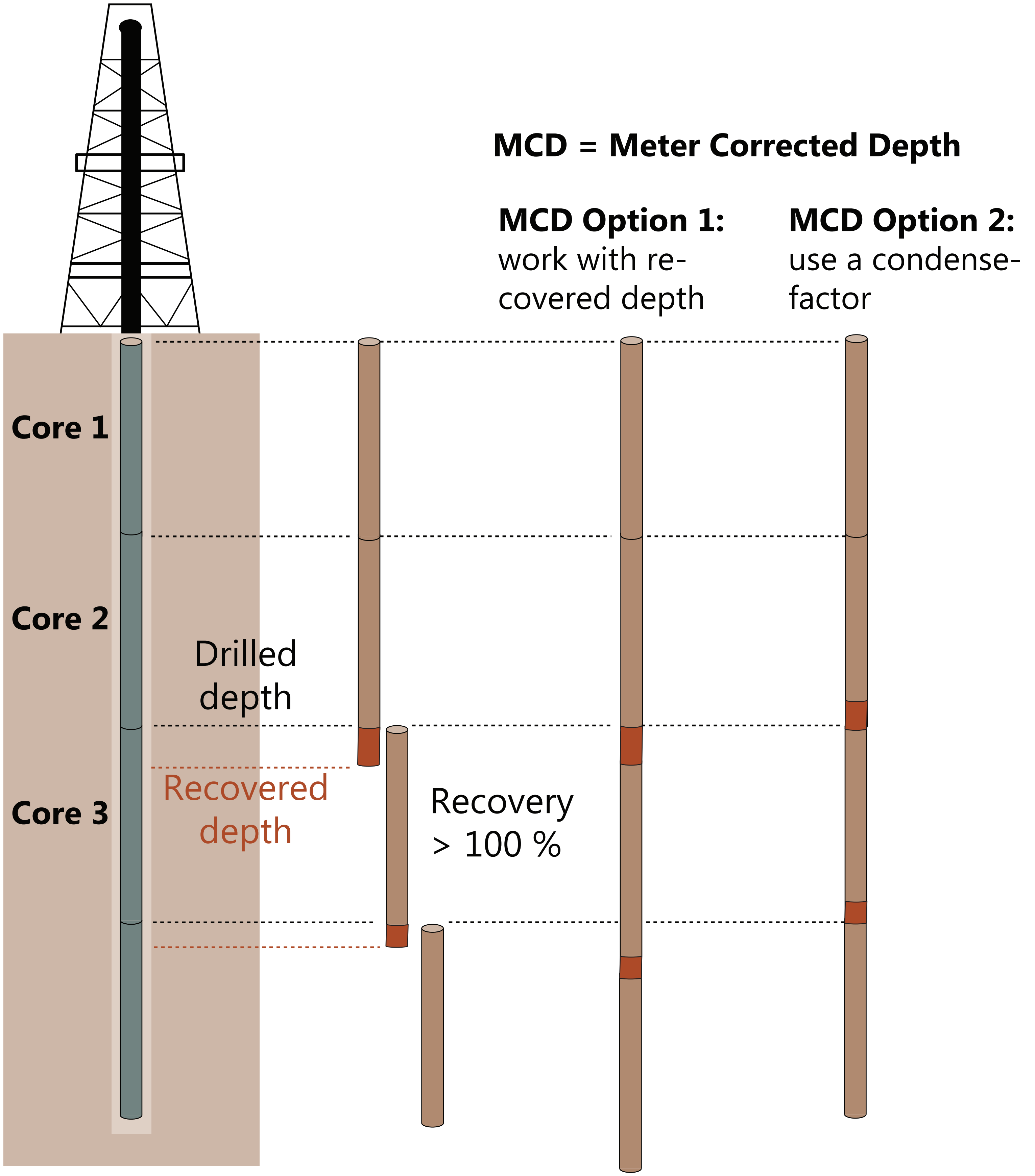
# Core Sampling



# Spliced record construction



# Drilled depth vs. Coring length



icdp

# Oman Drilling Project
# -Sampling the Samail Ophiolite-

oman drilling project

## Application Period

2011: Proposal → 2011: Workshop 1 → 2012: Workshop 2 → 2013: Sc. Paper Publication → 2014: 2. Proposal (approved)

**Principal Investigators (PIs)**

**Science Team**

## Field Work

**Drilling Operation Phase 1**
Dec 2016 - March 2017
4 cored holes
2 rotary holes
ca. 1500 m drilled length
**Downhole Logging Phase 1**

**Drilling Operation Phase 2**
Nov 2017 - March 2018
5 cored holes
4 rotary holes
ca. 1700 m drilled length
**Downhole Logging Phase 2**

**Hydrological borehole tests Phase 3**
January 2019

- Ca. 10 scientists on site
- One day shifts, ca. 7 am - 5 pm
- Drilling during the day shifts (no drilling on fridays)

On-site Workflow:

**Chief Geologist/ Manager**
- controls the workflow
- distributes tasks in the team
- takes care for **data dissemination**
- is in contact with the PIs
- is in contact with the drillers

Receiving the core from the driller;
Wash the core;
select the Micro-Bio sample

→ **Fitting Marking** Cut core run into sections
→ **Micro-Bio sampling** Analytical preparation
→ **Curation of Inventory** transfer into DIS delivery into core boxes
→ **360° scanning of sections**
→ **Sketching**
→ Initial **lithological description**
→ Taking off **reference samples;** label printing
→ **Imaging of boxes**
→ Packing of Boxes

Two simultaneously active drill sites; one for coring and the other for rotary drilling.
On-site scientists check progress at rotary drilling site and conduct the lithological description of the cuttings in addition to tasks at coring site.

On-site basic dataset is transfered to the ICDP website and provided to the entire science team. (oman.icdp-online.org)

## Lab Work

In advance:
- Public call for the Sampling Party
- Collection of Sample Requests

onboard the drilling vessel Chikyu under IODP standards in Japan

**Sampling Party Phase 1**
Jul 2017 - Sep 2017
**Leg 1** **Leg 2**

**Sampling Party Phase 2**
Jul 2018 - Sep 2018
**Leg 3** **Leg 4**

- Ca. 40 scientists per leg
- 24/7, 12 h shifts per group, 6 h offset between groups
- Ca. 50 sections described in 24 hours

The on-site data set is provided to the groups as background information

**Chief Team** [ **Co-Chiefs** **Staff Scientists**
- transfer knowledge, standards, rules and instructions
- decision about sampling
- time management

**Lab Manager**
- takes care for the lab facilities

**Group Leaders**
**Scientists**

**Publication Manager**
- collects all descriptions and data to compile visual core description

Lab Operations:

- Whole Round X-Ray CT; MSCL Scans
- Core Description: Igneous Group, Alteration Group, Structural Group
- Analysis of Discrete Samples: Geochemical Group, Physical Properties Group, Paleomagnetic Group
- Split Core MSCL; Infra-red Spectral Analyses
- Personal Sampling

## Reporting

Publication of reports in collaboration with publication manager following IODP standards

Publication of
**Operational** and **Science Reports**

**Acknowledgements**
This research used samples and/or data provided by the International Continental Scientific Drilling Program (ICDP) in the framework of the "Oman Drilling Project".

# XYZ DRILLING PROJECT

## SAMPLE REQUEST FORM
## for Moratorium and Post-Moratorium Requests

**To be completed by the Coordinating PIs and the Core Curator (moratorium requests only):**

**Please indicate the fate of this request.**

**[ ] approved** **[ ] deferred** **[ ] rejected**

**If this request is rejected, please include a brief explanation that can be quoted to the requestor.**

.................................................. ..................................................
**PI/Core curator signature** **PI/Core curator signature**

---

1. Expedition name: **XYZ Drilling Project (Expedition ID)**

2. Primary investigator contact information:

   Name:

   Office address:

   Phone:

   E-mail:

3. Please tick one of the following:

   Primary investigator is part of the Science Party [ ]

   Primary investigator is a Post-moratorium Researcher or external scientist [ ]

4. Is your sample request:

   Within the moratorium period? [ ]

   After the moratorium period? [ ]

5. Co-investigator(s) contact information (if applicable):

Name:

Office address:

Phone:

E-mail:

Name:

Office address:

Phone:

E-mail:

Name:

Office address:

Phone:

E-mail:

Name:

Office address:

Phone:

E-mail:

Name:

Office address:

Phone:

E-mail:

Name:

Office address:

Phone:

E-mail:

6. Type of sediment/rock and designated site (list of drill sites and holes)

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| Rock Type A | [ ] | *site/hole* | [ ] | *site/hole* | [ ] | *site/hole* | [ ] |
| Rock Type B | [ ] | *site/hole* | [ ] | *site/hole* | [ ] | | |
| Rock Type C | [ ] | *site/hole* | [ ] | *site/hole* | [ ] | | |
| etc. | | | | | | | |

7. Purpose(s) of request: Please summarize the nature of the proposed research concisely in 5-7 lines (this summary will be included in various official reports.) Provide a detailed description of the proposed research, including techniques of sample preparation and analysis, roles of individual investigators, etc., on an attached sheet. The detailed description of the project will be employed in reviewing the sample request and may be copied to other off-ice scientists.

8. Please describe the proposed core-sampling program in sufficient detail so that those who must prepare the samples for shipment will understand your needs. Please indicate if sampling in the composite profile is necessary (otherwise samples may originate from overlapping cores). Specify any other information that will be helpful in conducting your sampling program.

Sample Program: Number of samples _____

[ ] per core meter
[ ] per site
[ ] from the composite profile

Total number of samples you can analyze
within 1 year: ______________________ or
Particular stratigraphic or lithologic units to be sampled: ______________________
Sample size volume ($cm^3$): ______________________ or
dry weight (g): ______________________

9. Please describe any **specialized** sampling or processing techniques that you plan to be used, including specialized supplies or equipment required. Will you participate in the sampling? Will you send or bring special items with you to the hosting core repository, or do you expect them to be available?

**Primer 5**
Sample and Data Policies

# ICDP Sample, Data and Obligations Policy

## for Project XYZ

# ICDP Sample, Data and Obligations Policy for Project XYZ

**Table of Contents**



adapted from the corresponding ODP/ IODP publications (http://www-odp.tamu.edu/publications/policy.html and http://iodp.org/policies-and-guidelines)

# 1. Policy Overview

This document outlines the policy for distributing samples and data of the International Continental Scientific Drilling Program (ICDP) “XYZ Deep Drilling Project“ to research scientists (Science Party members and post-moratorium researchers) and the obligations that recipients of these samples or data incur. The specific objectives of the ICDP policy are to

1. Ensure availability of samples and data to Science Party members so they can fulfill the objectives of the drilling project and their responsibilities to ICDP;
2. Encourage scientific analyses over a wide range of research disciplines by providing samples to the scientific community;
3. Ensure that dissemination of the scientific findings of this ICDP drilling project are planned so as to gain maximum scientific and public exposure;
4. Preserve core material as an archive for future description and observations, nondestructive analyses and sampling.

There are two categories of policy users: (1) Science Party members and (2) post-moratorium researchers. Section 2 (Policy Guidelines) provides details for these users on how to submit sample requests and the specific reporting obligations that sample and data recipients incur.

# 2. Policy Guidelines

## 2.1. Guidelines for Science Party Members

### 2.1.2. Submitting Sample Requests

No sampling allowed without sample requests: Therefore Science Party members (see definition in section 3.1) may submit sample requests to ICDP prior to the expedition. However, sample requests will also be considered during the expedition and within the moratorium period. The Sample Request Form is available at the ICDP web site (www.icdp-online.org). The sample requests will be reviewed by the Coordinating PIs and the Core Curator and approval will be based on compatibility with the Sampling Strategy (see section 4.1.). The sample requester may choose to appeal any decision by the Coordinating PIs and the Core Curator to the Curatorial Advisory Board (see section 3.11). If a conflict should arise over the allocation of samples during the moratorium period, expedition participants will have priority over those who did not participate in the expedition.

### 2.1.3. Accessing Data

The Science Party may access expedition data online at a password-protected Web site provided by the ICDP during the moratorium period.

### 2.1.4. Obligation

All Science Party members are obligated to conduct research and publish the results of their work. To fulfill the obligation, papers must be published in a peer-reviewed scientific journal or book that publishes in English. To fulfill the obligation, manuscripts must be submitted within 24 months after the moratorium ended. Following completion of sample investigations, or in the event that research is discontinued, non-destroyed sample material must be returned within a maximum of 36 months after sample receipt at the investigator’s expense to the core repository (Core Repository, Institution; see section 4.4 for sample distribution information).

If Science Party members are unable to fulfill their obligation because appropriate samples or data were not retrieved during the expedition, or because data could not be obtained during post-expedition analyses, a letter of explanation must be submitted to the Core Curator. The letter must provide specific reasons for not fulfilling obligations such as lack of conclusive analytical results (quality or quantity), personal reasons or external factors. Pending the situation an extension of the obligation period up to one year can be requested. The request will need to justify the reasons for the extension and document the plan for releasing data obtained from ICDP samples within the extension period. The request will be considered by the repository curator.

### 2.1.4.1. Submitting Manuscripts during the Moratorium Period

Science Party members who wish to submit manuscripts or abstracts for publication before the moratorium period has expired must comply with the following guidelines:

1. Receive prior written approval by the Editorial Review Board (ERB, see section 3.12). This approval will be confirmed by the Coordinating PI who will circulate the manuscript among the expedition participants, tabulate the responses, and notify the author of the decision.
2. Use the authorship "**XYZ** Scientific Party"
3. Comply with all written collaborative agreements identified in the sampling strategy (see section 4.1).
4. Include the words "International Continental Scientific Drilling Program" or "ICDP" and "**XYZ**" in the abstract.
5. Acknowledge ICDP using the following wording: "This research used samples and/or data provided by the International Continental Scientific Drilling Program (ICDP) in the framework of the "**XYZ** Deep Drilling Project". Funding for this research was provided by the ICDP, list of funding agencies."
6. Provide the following key words to the manuscript publisher: "International Continental Scientific Drilling Program" or "ICDP" and "**XYZ**".
7. Notify the ERB of manuscript acceptance and submit complete citation information (see section 5 for contact information).

### 2.1.4.2. Submitting Manuscripts after the Moratorium Period

Science Party members who submit manuscripts for publication after the moratorium period has expired must comply with the guidelines as given in section 2.1.4.1. except for the first two guidelines.

## 2.2. Guidelines for Post-moratorium Researchers

Post-moratorium researchers who wish to conduct research on **XYZ** core materials may submit sample requests after the moratorium period has expired. The **XYZ** Sample Request Form is available ICDP web site (www.icdp-online.org). Obligations as explained in section 2.1.4. apply accordingly.

## 2.3. Guidelines for a Publication Succession

Publications of the scientific results should follow the following succession

1. PIs and leading field scientists publish "Science Reports" in the Scientific Drilling journal, supplemented by a detailed Operational Report, and the basic datasets with explanatory remarks as digital copies and corresponding landing pages on the Web.
2. These publications are under Open Access using Creative Commons licenses CC-BY, or CC-BY-SA accomplished with DOI and IGSN persistent identifiers.
3. PIs and key scientists summarize major scientific findings in a joint article in a high-ranked journal such as Nature or Science soon after sampling ended and first results are obtained.
4. All science groups publish a coordinated collection of articles on the various subjects involved as a special

volume of an international scientific journal or book at the end of the moratorium.

5. Finally, all are free to publish their individual results according to section 2.1.4.

# 3. Terms and Definitions

## 3.1. Science Party

The Science Party includes all scientists that participate in the field expedition and/or during sampling and that participate as co-PIs in a proposal that contributes to the funding of the drilling operation. Additionally, other scientists who have been approved by the Coordinating PIs for working on expedition material during the moratorium period and for publishing their research results are part of the Science Party.

## 3.2. Moratorium Period

The moratorium period is two years long and begins after the conclusion of the sampling (date **TBA**). During the moratorium period, the only researchers permitted to receive expedition core materials and data are members of the Science Party. After the moratorium period ends (post-moratorium period), samples can be given to persons whose requests have been approved by the Core Curator and Coordinating PIs.

## 3.3. Archive and Working Halves

Sediment cores are split into two halves for measurements and sampling. The halves are referred to as the "working half" and the "archive half." The entire working half is available for sampling. The concept and definition of an archive half is designed to enhance scientific flexibility and to enable greater access to important material. In certain circumstances the archive halve is available for sampling.

## 3.4. Composite Splice

Lake drilling expeditions typically recover sediment cores from multiple holes cored side by side at a given site. A composite stratigraphic depth section is constructed by establishing correlations between adjacent drill holes, using the variations in physical properties measured on cores by non-destructive sensors. A composite depth table describes the resulting depth offsets between holes. These offsets represent the difference between the meters below lake floor or ground level (mblf, mbgl; i.e., cored depth) and the meters composite depth (mcd) values that are derived from these correlations. Another data table describes the unique intervals in specific holes at a given site that have been used to construct the "ideal" section, also known as the "composite splice." The purpose of a composite splice is to describe the most complete sedimentary section at a given site, without gaps in core recovery (i.e., missing sediment), which then can be used for developing high-resolution sampling strategies and analyzing time series.

## 3.5. Permanent Archive

A "minimum permanent archive" is established for each ICDP drill site. Archive core earmarked "permanent" is material that is initially preserved unsampled and is conserved in the core repository for subsequent non-destructive examination and analysis. In "unique intervals" this minimum permanent archive consists of at least one half of each core. If so desired, the Coordinating PIs may choose to designate more, but not less, than this amount as the permanent archive. In "non-unique intervals", the permanent archive will consist of at least one half of one set of cores that span the entire drilled sequence. The permanent archive is intended for science needs that may arise five years or more after drilling is completed.

In practice, if holes are cored continuously, the minimum permanent archive may consist of one half of each core taken from the deepest hole drilled at a site. As such, the archive halves of cores from additional holes drilled to equal or shallower depths that contain replicate copies of stratigraphic intervals constituting the minimum permanent archive need not be designated as permanent archive, but can be, if so desired by the Coordinating PIs. If not deemed permanent archive, these cores are a "temporary archive". If a composite splice section is constructed and the sampling demand exceeds the working half, an alternative curatorial strategy may be required to ensure that all samples can be taken from the spliced section. In this case, the permanent archive can be defined from cores that are not part of the splice (e.g., from cores from different holes). Sampling of the permanent archive is feasible five years after the initial sampling party if the working and/or temporary archive halves of the core have been depleted.

## 3.6. Temporary Archive

Cores taken from non-unique intervals that are not part of the "minimum permanent archive" will be considered "temporary archives" unless stipulated otherwise in the Sample Strategy. If split, the temporary archive may be sampled just as the working halves are when (a) either the working halves have been depleted by sampling or (b) when pristine, undisturbed material is needed for special sampling needs, such as taking U-channels or slab samples.

## 3.7. Critical Intervals

Critical intervals are lithologic spans of such scientific interest that there is an extremely high sampling demand for them. These intervals may vary from thin, discrete horizons to thick units extending over an entire core or more. Examples include, but are not limited to sediment-basement contacts, igneous contacts, marker ash horizons, magnetic reversals, particular climatic transitions, and the transition from the impact breccia to the lake sediment. The Coordinating PIs are responsible for anticipating the recovery of critical intervals and for developing a strategy for sampling and/or conserving them. For post-moratorium sampling, the Core Curator will work with investigators to ensure that previously defined critical intervals are sampled only when necessary.

## 3.8. Unique and Non-unique Intervals

A cored interval is designated "unique" if it has been recovered only once at a drill site. The most common occurrence of a unique interval is one that results when only one hole is drilled at a site. If the cored interval is recovered from two or more holes, then the interval is considered "non-unique". A critical exception to this definition occurs when drilling into e.g. igneous basement rocks. Every hole drilled into this lithology is considered unique because of its inherent lateral heterogeneity. Lithostratigraphic analysis of piston cores from multiple holes drilled at one site may reveal that short sedimentary intervals (generally less than 2 m) are missing between successive cores from any one drill hole, even where nominal recovery approaches 100%. These missing intervals can be ignored when considering whether or not an interval is unique.

## 3.9. Non-destructive Analyses

Requests to perform non-destructive analyses on cores (e.g., descriptions, imaging, X-rays) should be submitted to the Core Curator and the Coordinating PIs by completing the **XYZ** Sample Request Form. Investigators who conduct non-destructive analyses incur the same obligations as scientists who request samples.

## 3.10. Core Curator

There are three different Core Curators for the **XYZ** Drilling project: one for lake sediments, one for permafrost deposits, and one for impact rocks. The Core Curator has responsibility for the preservation of the core once it arrives at the repository and to oversee the use of core material after the moratorium period ends. He/She maintains records of all distributed samples, both from the platform and from the repositories. Sample records include the names of the recipients, the nature of the proposed research, the volume of samples taken and the status of the request. This information is available to investigators upon request through the Core Curator.

## 3.11. Curatorial Advisory Board

The Curatorial Advisory Board (CAB) consists of members of the scientific community that actively supported the funding of **XYZ** drilling operations (see section 5). The **XYZ**-CAB has two main roles:

1. Act as an appeals board vested with the authority to make final decisions regarding sample distribution if and when conflicts or differences of opinion arise among any combination of the sample requester, the Core Curator and the Coordinating PIs.
2. Review and approve requests to sample the permanent archive.

A person appealing to the CAB may contact any member of the board directly.

## 3.12. Editorial Review Board

The Editorial Review Board (ERB) is comprised of the Coordinating PIs, the Core Curator and all Co-PIs who actively funded the **XYZ** drilling operations. The ERB has four main roles:

1. Coordinate the writing of the drilling project results;
2. Monitor all post-drilling project research and associated publication of results;
3. Make decisions on issues relating to the publication of research related to the drilling project;
4. Monitor obligation fulfillment by the Science Party.

# 4. Curatorial Procedures

## 4.1. Sampling Strategy

To ensure the best possible use of the core and distribution of samples, a sampling strategy is developed for each drilling project during pre-expedition planning. The strategy will integrate and coordinate the programs for drilling, sampling, and downhole measurement to best meet the drilling project's objectives and the scientific needs of the Science Party. The strategy may evolve during the expedition and the moratorium period.

## 4.2. Expedition-Specific Sampling Strategy Guidelines

Once a proposal has been scheduled for drilling, a formal expedition-specific sampling strategy is agreed that meets the specific objectives of the expedition and defines the minimum permanent archive. The Sampling Strategy becomes the basis of the sampling plan used during the moratorium period.

A successful sampling strategy will

1. Define the amount of core material available to the Science Party for sampling by deciding if and when more than a minimum permanent archive is needed;
2. Anticipate and possibly define limits on the volume and frequency of sampling for routine analyses, pilot studies, and low-resolution studies;
3. Estimate the sampling volume and frequency that is needed to meet the objectives of the expedition, as per scientific sub discipline and request type;
4. Anticipate the recovery of critical intervals and develop a protocol for sampling and/or preserving them;
5. Propose where and when sampling will occur;
6. Determine special sampling methods and needs e.g., microbiology;
7. Consider any special core storage or shipping needs (e.g., plastic wrap, freezing sections);
8. Identify disciplines/personnel needed for sampling.

# 4.3. Sample Request

## 4.3.1. Procedures for Requesting Samples

Requests for samples should be submitted using the **XYZ** Sample Request Form. To assist the sample requester the Core Curator may provide advice and guidance to the requester when considering sample volumes and frequencies as well as relevant information about previous sample requests and resultant studies on specific core intervals.

### 4.3.1.1. Moratorium Period Sampling

During the moratorium period, only members of the Science Party receive samples.

### 4.3.1.2. Post-moratorium Period Sampling

After the moratorium period has expired, samples may be provided to any researcher with the resources to complete a scientific investigation.

## 4.3.2. Sample Request Approval

### 4.3.2.1. Moratorium Period Sampling

After reviewing the sample requests, approval will be based on compatibility with the sampling strategy. In cases where a sample request is considered incompatible, several options are possible: (1) recommend modifications to the request, (2) modify the sampling strategy, or (3) reject the request if the other options are inappropriate. If a conflict arises over the allocation of samples during the moratorium period, expedition participants have priority over other scientists in the Science Party.

### 4.3.2.2. Post-moratorium Period Sampling

The Core Curator will evaluate post-moratorium sample requests for completeness and adherence to the provisions in this policy. When considering a sample request, the Core Curator will ascertain whether the requested material is available in the working half or the temporary archive half of the core. If the material is unavailable, the Core Curator will consult with the requester to determine if the range of the requested interval(s) or the sample spacing within the interval(s) can be modified. If the request cannot be modified because of scientific requirements, a request to sample the permanent archive will be considered.

Approval of sample requests will be based on the availability of material and the length of time it will take the investigator to complete the proposed project. Typical studies will take two to three years, but a study of longer duration will be considered under certain circumstances.

## 4.4. Sample Distribution

Sample requests are processed differently depending upon whether they are field-based, moratorium or post-moratorium. Field-based and moratorium sampling steps are outlined in section 4.3. Post-moratorium Sample Requests are processed in order of approval. This approximates the order of submission and receipt of requests, however the review and approval process may cause certain requests to be delayed for various reasons, e.g., lack of available material causing a discussion and revision of which cores to be sampled. In addition, after approval, other factors may cause requests to be processed out of order, e.g., a request for thousands of samples may take several weeks of labor to complete, whereas requests for small numbers of samples may take only hours. When different sized requests are pending at the same time at the core repository, small requests may be completed before or during the work on a large request, so that they are not all held up by the large request. Requests that are tied to visits to the repository by the requester are dependant upon the schedule of that visit. Most requests of small to moderate size and complexity may be expected to be processed within a month.

# 5. Contact Information

Here only names and email addresses are provided as contact information. For more details, please consider the ICDP website

Coordinating PIs:

**List of PIs (names, afflliation, e-mail)**

Core Curator:

**List of core curators (names, afflliation, e-mail)**

Curatorial Advisory Board (CAB):

**List of CAB members (names, afflliation, e-mail)**

Editorial Review Board (ERB):

**List of ERB members (names, afflliation, e-mail)**

# Risk Analysis Matrix for ICDP Projects

**ICDP Primer 5**
Supplement 11

| Negligible | Low | Moderate | High |
|---|---|---|---|

## General Risks (based on previous ICDP project issues)

| No | Description | Likeli-hood | Impact | Risk Pot. | Mitigation Strategy | Likeli-hood* | Impact* | Risk Pot.* |
|---|---|---|---|---|---|---|---|---|
| **A** | Delays, due to weather, incidents, permits | High | Low | Mode-rate | Flexible planning w/ variable time plans | Mode-rate | Low | Low |
| **B** | Cost overrun | High | Low | Mode-rate | Professional project management, better site survey, contingency funding (due diligent preparation) | Mode-rate | Low | Low |
| **C** | Missing 3rd party funding | Mode-rate | High | High | Planning in phases or de-scoping opts | Low | High | Mode-rate |
| **D** | Understaffing | Mode-rate | Mode-rate | Mode-rate | Prof. project management, training courses, reducing on-site science to the minimum, increase budget | Low | Low | Low |
| **E** | Poor engineering planning and operational management | High | High | High | Prof. project management, training courses, implementation of drilling-well-on paper (DWOP) and QHSE procedures | Mode-rate | Mode-rate | Mode-rate |
| **F** | Unexpected geology | High | Mode-rate | High | Better site survey, flexible planning, contingency drill plans, <DWOP> | Mode-rate | Low | Low |
| **G** | Missing or short supplies of services and equipment | High | Mode-rate | Mode-rate | Prof. project management, detailed planning w/ Plan B | Low | Mode-rate | Low |
| **H** | Missing coordination | Mode-rate | Low | Low | Detailed planning workshops with all groups involved, DWOP, professional wellsite management | Low | Low | Low |
| **I** | Missing communication in Science Team and with OSG | High | Mode-rate | Mode-rate | Prof. project management with constant updates, involvement of key players, detailed planning workshops with all groups involved, kick-off meeting | Low | Mode-rate | Mode-rate |
| **J** | Late recognition of obstacles | Low | Mode-rate | Low | Early warning, daily communication between groups on site | Low | Low | Low |
| **K** | Missing documentation and reporting | High | Mode-rate | Mode-rate | Require DIS utilization and Initial Science Report in SD | Mode-rate | Low | Low |
| **L** | Missing safety planning and implementation | Mode-rate | High | High | Require safety planning in JRV according to host countries law, implementation of QHSE strategy and procedures | Low | Mode-rate | Mode-rate |
| **M** | Loss of equipment, loss of hole | Mode-rate | High | Mode-rate | Drilling engineering well planning, written operational procedures on site, DWOP, insurance coverage Contingency funding, Plan B | Low | Mode-rate | Mode-rate |
| **N** | Injury and/or fatality | Low | High | High | Increase safety planning and implementation | Negligible | High | Low |
| **O** | No public acceptance, NIMBY | Mode-rate | High | High | Outreach actions before drilling | Low | High | Mode-rate |

* risk after treatment

**Individual Project Risk Matrices** should be provided by each project for input, review and advise as part of the proposal and again a few months before drilling starts specifically for technical and operational planning. OSG will provide instructions and examples to help PIs setting up such scheme and implementing necessary measures. EC (or OSG on behalf of EC) should review and approve defined milestone and deliverables; OSG acts as consultant for the project PIs but not as project manager. Only projects with specific technical and operational risks will fall into this category. Projects with approved techniques and experienced oversight staff and contractors will not fall under this category. Future JRVs will include this procedure.

# Risk Analysis Matrix for ICDP Projects

| Negligible | Low | Moderate | High |
|---|---|---|---|

Drilling Risks (based ICDP project issues)

| Section | Stratigraphy | Geological Challenge | Scenario to Evaluate | Likelihood | Damage | Risk Classification | Preventive Actions | Likelihood after Prevention | Resultant Damage | Minimized Risk |
|---|---|---|---|---|---|---|---|---|---|---|
| Conductor casing (0 – 50 m) | Quaternary | Hardrock boulders | Hard formation, poor bit performance, low core recovery, time delay: 1 day | Probable | Low | | Pilot hole drilling with small diameter bit, use of low flow rates and bentonite mud | Low | Low damages in bit | |
| Casing (50-1000 m) | Tertiary | Boulders and sediments, adverse stress orientation | BHA verticality, impossible to core more than 1 m | Probable | Low | | BHA packed w/ 2 stabilizers, mud with bentonite | Low | Low damages in drill string | |
| | Jurassic | Swelling clays and shales | Bit balling, stuck pipe, low rate of penetration, poor coring, time delay: 1 week | Probable | High | | Mud combines with inhibitors, cleaning pills | Low | Damages in drill string and bit | |
| | | Unconsolidated sediments | Loss of fluids, stuck pipe, gas inflows, hydrocarbons presence, poor coring, 1-week lost time | Probable | High | | Increased mud weight, use of inhibitors, polymers, circulation schedules, controlled drill parameters | Low | Surface equipment damage, drill string damage, bit damage | |
| | Triassic | Swellable clays and shales | Bit balling, stuck pipe, low rate of penetration, time delay: 1 day | Probable | Low | | Mud combined with inhibitors, cleaning pills, learning curve | Low | Damages in drill string and bit | |
| | | Intrusive magmatics | Bit damage, loss of circulation, lost BHA, no core | Probable | High | | Changed bit, slowed rotation, less weight on bit | Low | Bit damage | |

# Quantification Matrix for Risk Analysis

| | | | Probability of Occurrence | | | | |
|---|---|---|---|---|---|---|---|
| | | | Very Unlikely | Unlikely | Very Likely | Probable | Almost Certain |
| | | Case | >5% | 5%-25% | 25%-65% | 65%-95% | >95% |
| Damage Extent | **Severe Damage** | >3 months delay, serious injury, >65% adl. costs, loss of well, environmental damages, lost reputation | | | | | |
| | **High Damage** | >1 month delay, injury, high 15%- 65% additional costs, loss of well section, side track, fishing | | | | | |
| | **Middle Damage** | >1 week delay, minor injury, 15%- 35% extra costs, missing well section, side track, fishing | | | | | |
| | **Low Damage** | >1 day delay, 5% -15% extra cost, missing a well section, fishing | | | | | |
| | **Very low Damage** | Low time loss, lower additional costs (<5%) | | | | | |

| | |
|---|---|
| Risk acceptable, no necessity to minimize/eliminate risk potential | |
| Risk to be lowered as reasonably practicable, careful evaluation | |
| Risk intolerable, must be eliminated/reduced by minimizing impact of damage and likelihood of occurrence | |

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