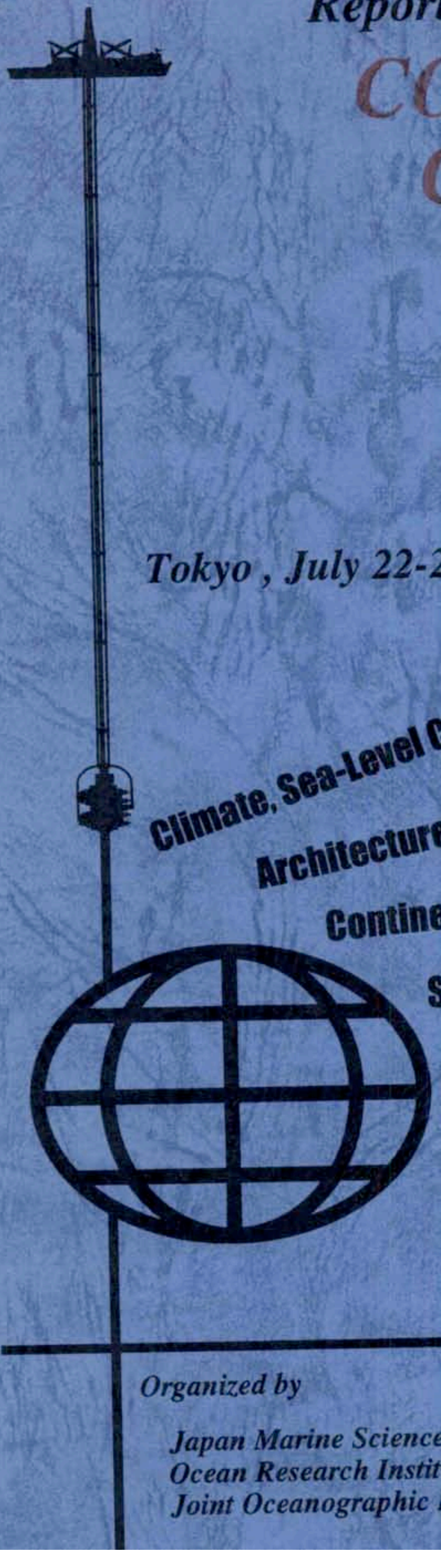

Report of the

CONference on Cooperative Ocean Riser Drilling

Tokyo , July 22-24 , 1997

Climate, Sea-Level Change, and Deep Biosphere

Architecture of Ocean Lithosphere

Continental Rifting and Large Igneous Provinces

Subduction and Earthquake Processes

Borehole and Seafloor Observatories

Drilling and Tool Technology Development

Organized by

Japan Marine Science and Technology Center (JAMSTEC)
Ocean Research Institute, the University of Tokyo (ORI)
Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES)

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CONCORD PREFACE

The Conference on Cooperative Ocean Riser Drilling was initiated through a Joint meeting between the Executive Committee (EXCOM) of JOIDES (Joint Oceanographic Institutions for Deep Earth Sampling) and the Science and Technology Agency (STA) / Japan Marine Science and Technology Center (JAMSTEC) in January 1996. This joint meeting addressed the Japanese proposal to construct a new, riser-equipped deep sea drilling vessel, the so-called OD21 project. The EXCOM recommended that the JOIDES Planning Committee (PCOM, now SCICOM: Science Committee) and OD21 proponents organize a series of discussions on scientific research as soon as possible. The discussions should identify the relationship between the future goals of the ODP and OD21 Science Programs.

PCOM, JAMSTEC and Ocean Research Institute, University of Tokyo (ORI) agreed to organize a steering committee for an international conference to clarify the scientific objectives of OD21 and nominated the committee members. The first Steering Committee took place in Tokyo October 31, 1996, immediately following the International Workshop on Riser Technology in Yokohama. The Steering Committee decided that the purpose of the conference was to bring together the international scientific community to discuss how riser-supported drilling in the ocean can address high priority scientific objectives within the various themes of the ODP Long Range Plan, and how a phased technology development of OD21 riser drilling can be achieved. The Committee also decided that the conference should compose of five scientific working groups and one working group dedicated to engineering related to deep riser drilling. EXCOM, in February 1997, endorsed the proposed plan to organize CONCORD. The second Steering Committee took place in Copenhagen April 10 to 11. The Steering Committee assigned co-chairs to six working groups and established the schedule of the conference. It also decided the procedure for preparing the proceedings of the meeting and requested scientific vision statements to be submitted by all meeting participants prior to the conference.

CONCORD was held at the National Olympics Memorial Youth Center in Tokyo on July 22-24, 1997, supported by STA, the Japanese Ministry of Education, Science, Sports and Culture (MONBUSHO) and all present ODP members. In attendance were over 150 leading geoscientists, microbiologists, deep-sea drilling engineers and earth science program executives from 17 different countries. Prior to the conference, geological excursions were conducted at the following three areas, Tanzawa Terrane, Mt. Hakone and Oshima Island, and Kobe.

The conference proceeded in the following manner. After the welcome address by Takuya Hirano, president of JAMSTEC, Hans Christian Larsen, Co-Chair of the conference with Ikuo Kushiro, presented the opening remarks and defined the objectives of the conference. Then, Shigeru Aoe, Director-General of the Research and Development Bureau of STA, Yasuhumi Sakitani, Vice Director-General of the Science and International Affairs Bureau of MONBUSHO, and Robert W. Corell, Assistant Director of the US National Science Foundation, presented opening addresses stressing the importance of scientific ocean drilling in the next century. After this opening ceremony, Professor Xavier Le Pichon, France, presented a keynote address entitled "Solid Earth Science and Deep Sea Drilling". Professor Le Pichon, one of the founders of the plate tectonic paradigm emphasized that in Earth science "the oceans are still where the action is".

Following the opening, the riser drilling system and the construction and development plan of the OD21 drill ship were reviewed, the new ODP Long Range Plan was presented, and the themes and mandates of the working groups were introduced. Working group discussions were held over the next two days with short plenum sessions securing coordination between the six working groups. Then at the third day's Plenum Session, the final reports of each working group were presented. At the same time, the official CONCORD statements were discussed and adopted by the conference.

After the conference, the Steering Committee, Working Group Chairs and selected individuals drafted the meeting proceedings at the Hamayu Lodge of Kurabuchi-mura in Gunma Pref. from July 25 to 27. The report consists of four parts : the executive summary of CONCORD, an introduction, the CONCORD Statements, and position papers for the six working groups.

Hans Christian Larsen Ikuo Kushiro
Co-Chairs, CONCORD Steering Committee

Executive Summary

The Conference on Cooperative Ocean Riser Drilling (CONCORD) agreed that the understanding of major earthquake processes through direct observation and monitoring should be the first priority of a new riser drillship.

Over 150 leading international Earth scientists and drilling engineers reached a clear consensus on the need for a new generation deepwater drilling vessel, equipped with a riser, or riser-type system, that can circulate drilling fluids, provide well control, and thus allow access to deeper and more challenging Earth environments. This major research facility, proposed by the Japan Marine Science and Technology Center (JAMSTEC), will open up a new and exciting phase of scientific exploration, with consequent societal and economic benefits. Japan's commitment to this major capital investment was universally welcomed by CONCORD participants, and is seen as evidence of its emerging leadership in marine science.

CONCORD was held in Tokyo, Japan, 22 to 24 July, 1997 and participants identified a range of fundamentally important scientific problems that can be addressed only by drilling deeper into the Earth. Key problems identified further include:

- searching for new species of ancient, but still living bacteria that lie deep within marine sediments and oceanic crust;
- extending the record of natural climate variability to at least 180 million years before present, and the determination of the history of, and environmental conditions associated with significant past "greenhouse" climate events and related sea level change;
- the record of past "super volcanic" events in the ocean basins, their relation to the dynamics of the deep Earth, and their impact on global climate;
- the nature of oceanic crust, which constitutes two-thirds of the Earth's surface, the dynamics of its formation and alteration, including drilling through the entire crust and into the upper mantle of the Earth (the "21st Century Mohole"); and
- the formation of continents, the break-up of the continents, and the evolution of their sedimentary basins along margins, many of which are rich in hydro-carbon deposits.

Achieving many of these objectives will require installation of arrays of sub-surface deep-sea observatories that can monitor our dynamic and evolving Earth.

Resolution of these important scientific problems is critical to achieving a better understanding of the dynamic processes that shape the planet's surface, cause earthquakes and volcanism, control formation and distribution of petroleum and mineral resources, and regulate Earth's climate.

CONCORD participants were in full agreement that resolution of the above key scientific problems lies deeper than previously drilled. It requires a concerted international scientific effort, which must highlight deep drilling. Riser, or riser-type drilling, involving circulation of dense, viscous drilling fluids, is critical for well stability and sub-surface fluid control. Nonetheless, there will be a continuing role for a drilling vessel that is not equipped with a riser, and is similar to that operated by the current Ocean Drilling Program (ODP). Such a drillship is necessary for ongoing, high resolution sediment studies and exploration of shallower crustal sections. It can also provide pilot holes that support later riser drilling. A multiple platform, scientific ocean drilling program beyond 2003, as envisaged in the 1996 ODP Long Range Plan, was endorsed at CONCORD. The participants encouraged the emerging cooperation between Japan, the United States, and other ODP partner countries in making possible a future Integrated Ocean Drilling Program (IODP), and encouraged even wider international involvement.

The new generation deepwater drilling vessel proposed by JAMSTEC should be equipped initially with a riser, that will enable controlled drilling and rock core recovery in 2,500 to 3,000 meters of water, and up to 7,000 meters beneath the sea bed. CONCORD urged that the new drillship be available by 2003, and encouraged further development of appropriate technology, which will eventually enable riser-type drilling in at least 4,000 meters of water. To ensure that this new scientific research facility is at the leading edge of technology, JAMSTEC will continue to both work in close cooperation with commercial deepwater petroleum exploration drilling operators and further develop links with ODP.

INTRODUCTION

Scientific ocean drilling has been an integral part of marine geological research for the last thirty years. Most of the active processes that create and shape the crust of the Earth take place under the ocean. Drilling is the only way to access the deep layers within the Earth to learn directly about its structure, and to investigate the processes, such as plate tectonics and continental drift, that shape the ocean basins and continents. Furthermore, the most complete and undisturbed record of the history of climate and ocean circulation is archived within the sediments deposit on the seafloor, so obtaining long, detailed and continuous sediment cores is critical to unraveling the history and evolution of the Earth and its natural systems. With continued world population growth and expanding consumption of resources, developing an understanding of Earth's natural systems grows ever more pressing if we are to manage the global environment in the next century.

Our continued development of an understanding of the Earth presently involves two strategies. The first of these attempts to quantify plate tectonic processes, including the dynamics of the mantle that drives plate tectonics. The second responds to the growing awareness that in order to understand the dynamics of the planet Earth as a system, the complex relationships among the lithosphere, hydrosphere and atmosphere have to be unraveled through an interdisciplinary approach to our research efforts.

The international marine geoscience community has been successfully served by a single drilling platform throughout the lifetime of scientific ocean drilling. However, this has placed ever increasing constraints on our ability to pursue new scientific initiatives of increasingly diverse character. The types of problems that scientific ocean drilling is now poised to address will require new capabilities that will permit drilling much deeper and into unstable and fractured formations and overpressured environments.

With the Ocean Drilling Program (ODP) scheduled to end in 2003, the international community has already begun planning for the next era of scientific ocean drilling. In 1996, ODP published its Long Range Plan entitled "Understanding our Dynamic Earth through Ocean Drilling". This document identifies the fundamental scientific problems that will be addressed through drilling in both shallow and deep waters into the early part of the 21st century. Scientific goals focus on two overall scientific themes. The first is "Dynamics of Earth's Environment"; it encompasses a range of scientific problems related to understand how our planet's environment - in particular the atmosphere, hydrosphere, cryosphere and biosphere - changes in response to natural and anthropogenic perturbations. The second theme is "Dynamics of Earth's Interior", which seeks to examine the deeper structure of the Earth's outer layers, global mass and energy fluxes, mantle dynamics, and deformation processes at a wide range of scales.

In order to accomplish these scientific objectives, the successor to ODP is envisaged to be a multi-platform program with two major vessels; one with capabilities similar to those of the current drilling vessel, the *JOIDES Resolution*, and a second with the capabilities to control borehole conditions (referred to as riser drilling) thereby permitting drilling to greater depths and in difficult environments. The combination of these two platforms will provide the capabilities necessary to approach new types of scientific problems that have not previously been possible.

The desire for riser drilling has been the aspiration of the scientific drilling community for more than a decade. Since it was originally proposed at the Second Conference on Scientific Ocean Drilling (COSOD II) in 1987, JAMSTEC and the Japanese Science and Technology

Agency have been pursuing the possibility of building a new drill ship with deep water riser capability. The oil industry is routinely using riser technology for drilling in shallow water. However, extending riser capabilities to depths of several thousand meters is a major technological challenge, and cooperation and collaboration with the drilling industry will be extremely beneficial.

Since 1995, consideration of the Japanese proposal "Ocean Drilling in the 21st Century" (OD-21) has been closely integrated with the preparations by Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) for continued international ocean drilling beyond year 2003. In January 1997, the National Science Foundation, STA/JAMSTEC and MONBUSHO agreed on a framework for an Integrated Ocean Drilling Program beyond 2003.

The initial planning for the design and application of a riser-equipped drilling platform was completed at the International Workshop on Riser Technology held in Yokohama, Japan in 1996. The International Conference on Cooperative Ocean Riser Drilling (CONCORD) represents the next step in the planning process and was held on 22-24 July 1997 in Tokyo, Japan. More than 150 earth scientists and drilling engineers from 17 nations participated in the meeting.

SCIENTIFIC GOALS AND OBJECTIVES

Discussions at the CONCORD meeting were organized in a series of Working Group:

Group 1	Climate, Sea Level Change, and Deep Biosphere
Group 2	Architecture of the Oceanic Lithosphere
Group 3	Continental Rifting and Large Igneous Provinces (LIPs)
Group 4	Subduction and Earthquake Processes
Group 5	Borehole and Seafloor Observatories
Group 6	Drilling and Tool Technology Development

Reports and recommendations from each of these Working Groups constitutes the bulk of this report. Below a summary list of the science themes and experiments proposed by the CONCORD meeting for riser supported drilling is presented.

Main Themes

Discussions in Working Groups revealed the following to be the most essential themes and goals for the ocean riser drilling;

- •WG1 (Climate, Sea-Level Change, and Deep Biosphere)
  - Exploring the Base of the Deep Sub-sea Biosphere
  - The Extent and Nature of Gas Hydrates and Free Gas
  - The Uplift of Tibet/Himalayas and Initiation of the Monsoon
  - A Mesozoic Reference Section: Anchoring the Global Array
  - Sea-level Rhythms and Responses in the Greenhouse World
- •WG2 (Architecture of Ocean Lithosphere)
  - Ultra Deep Drilling of the Lower Oceanic Crust and Moho
  - Water-Rock Reactions and the Evolution of the Oceanic Crust
- •WG3 (Continental Rifting and Large Igneous Provinces)
  - Oceanic Plateaus
  - Mantle Dynamics and Lithospheric Deformation in Continental Breakup

- WG4 (Subduction and Earthquake Processes)
    - Dynamics of Subduction Zone Earthquakes
    - Subduction Initiation and Birth of the Continents
- WG5 (Borehole and Seafloor Observatories)
    - Long-term in-situ Monitoring of the Seismogenic Zone
    - Ocean Hydrogeology
    - Experiment Design: A New Tool for Multi-Level Multi-Parameter Hydrologic Monitoring/Testing/Sampling System
    - Infrastructure and Collaborations
- WG6 (Drilling and Tool Technology Development)
    - OD21 Preliminary Engineering Development
    - The Benefits of Riser Drilling
    - Technology Issues Arising from the Scientific Working Groups
    - Issues of Modification of Information and Contamination of Samples
    - New Technology Possibilities
    - Recommendations

The Transition to Riser Drilling: Some Advance Considerations

The advent of riser drilling will require fundamental changes in many aspects of scientific ocean drilling. Pre- (and occasionally post-) drilling site characterizations will be more comprehensive; more lead time will be required. The Scientific Advisory Structure will deal not only with a series of discrete "legs" for riserless operations, but with a variety of complex operations at and around individual riser sites, each occupied for at least months and perhaps years.

Site Characterization

The technological challenges and cost implications of riser drilling will far exceed those posed by ODP's riserless operation. Pre-drilling geophysical surveys will need to be much more exhaustive than those that have been conducted generally for ODP, in order to be sure both that the proper riser locations are chosen, and that they are well-characterized within the regional geologic environment. MCS surveys will be mandatory; in many instances, 3D surveys will be needed to augment 2D control. Even 4D surveying, e.g., for monitoring fluid flow regimes, may take place. Where possible, collaboration with industry is necessary to ensure that their databases, including neighboring well information and downhole logs, are accessed and integrated; in turn, scientific ocean drilling results may become more important in the global exploration for sub-seafloor resources. The seafloor environment at riser sites will need to be completely characterized in preparation for riser placement, e.g., by means of multibeam bathymetry/backscatter surveys, very high-resolution (including deep-towed) seismic profiling, and assorted geotechnical studies (including riserless drilling of pilot holes). Analyzing and interpreting such large data arrays will take up to 5 years; if riser drilling is to begin in approximately 2003, active surveying to prepare for it should begin as soon as possible.

Scientific Advice

One of the enduring legacies of JOIDES is its international scientific advisory structure, which over the last several decades has refined a system of proposal-based science in service of riserless drilling. In the early years of DSDP, global reconnaissance was the drilling focus. During ODP, such reconnaissance began to evolve towards longer-term drilling strategies, ranging from latitudinal transects for paleoceanography to offset drilling of tectonic windows in ocean crustal environments. However, the mode of operation of the *JOIDES Resolution* has remained more-or-less the same as that of the *GLOMAR Challenger*, a series of 1-2 months "legs" involving a variety of essentially stand-alone, discrete experiments. Scheduling the vessel's time each year to address multiple sites has been a primary responsibility of the JOIDES Advisory Structure. Such scheduling has never occurred more than 2 years in advance. Riser drilling will change that approach. Only a few sites (at most) will be drilled each year, and ancillary projects to ensure the greatest scientific return from potential sites may be planned many years in advance, by dozens of scientists from diverse disciplines. Therefore, science advice will probably concentrate less or evaluating large numbers of scientific proposals (from small groups of "proponents") and vessel scheduling, and more on coordinating long-term (pre- and post-drilling) surveying and downhole activities at the small number of selected riser sites. Other planning issues include multiple scientific staffing of the drillship and attendant logistics at these "natural laboratory" locations.

In many cases, the riserless and riser-equipped drilling platform operations will be linked; the former will "set up" the latter by establishing shallow pilot holes for subsequent riser emplacement and deep drilling. Such dual platform scheduling will be a more complex task than any JOIDES Advisory Structure has ever faced; new types of panel expertise may also be required. The present JOIDES structure should begin to address these issues immediately.

CONCORD RECOMMENDATIONS AND STATEMENT

The International Conference on Cooperative Ocean Riser Drilling (CONCORD) held in Tokyo, Japan, 22-24 July 1997 was attended by over 150 leading geoscientists, microbiologists, deep-sea drilling engineers and earth science program executives from 17 different countries. The Conference was organized by the International CONCORD Steering Committee, co-chaired by Dr. Hans Christian Larsen and Professor Ikuo Kushiro on behalf of the Japan Marine Science and Technology Center (JAMSTEC), Ocean Research Institute (ORI) of University of Tokyo and ODP/JOIDES and was co-sponsored by the Japanese Science and Technology Agency (STA) and the Ministry of Education, Science, Sports and Culture (MONBUSHO).

The main objective of the Conference is to document science that could be addressed by a riser-equipped drilling vessel of the type proposed by JAMSTEC.

Five scientific and one technological working groups discussed the following subjects:

1) Climate, sea level changes, and deep biosphere;
2) Architecture of the ocean lithosphere;
3) Continental rifting and large igneous provinces (LIPs);
4) Subduction and earthquake processes;
5) Borehole and seafloor observatories; and
6) Drilling and tool technology development.

CONCORD participants representing a broad diversity of research interests and countries, after considering the present state of earth sciences and technology development, **conclude that:**

1) Riser-type drilling is now indispensable for the continual development of humankind's understanding of the dynamic processes that shape our planet's surface, control the distribution of resources, and affect our environment and the biosphere through earthquakes, volcanism and climate change.

2) A broad diversity of fundamental scientific questions can be addressed by deep ocean riser drilling, including (in no priority of order):

--Understanding Earthquake Cycle by Direct Long-term Observation of Active Processes in the Seismogenic Zone
--The Deep Biosphere: Exploring the Lost World
--A Mesozoic Reference Section: Anchoring the Global Array
--Tectonics and Monsoon Development
--Rhythms of the Greenhouse World
--Ultra Deep Drilling of the Lower Oceanic Crust and Moho
--Water-Rock Reactions and the Evolution of the Oceanic Crust
--Mantle Dynamics, Global Change, and Rupture of Continental Lithosphere
--Dynamics of Subduction Earthquakes and Faulting
--Initiation of Subduction, Island Arc Evolution, and Birth of Continents
--Multi-Packer, Multi-Level, Multi-Sensor Observatory Development

3) Within these high-priority scientific themes identified by CONCORD, one particular experiment is unanimously selected and recommended by the Conference to be prepared for immediately, and the deep drilling required by this experiment should be allocated on the order of 1-2 years of initial drilling as soon as the vessel is available. The experiment chosen is a comprehensive study of an active seismogenic zone within a subduction zone system. The whole experiment, from planning through execution, is envisaged to be a concerted international effort providing an example of the future mode of international and global operation of the riser-equipped drilling vessel. This experiment has been chosen because of its outstanding scientific potential, readiness, societal relevance, and logistical suitability regarding water depths and potential sites close to the ship's home base, as required for the initial deployment and testing of the drillship.

4) Many of the aforementioned science objectives can be achieved using the initially envisioned riser length of 2,500-3,000 m. However, several of science objectives require a riser system capable of operating in water depths in excess of 4,000 meters. CONCORD strongly urges that JAMSTEC, with input from JOIDES and the drilling industry, evaluate applicable technologies for extending riser drilling capabilities into these greater water depths as soon as possible.

5) CONCORD is fully aware of the high costs required to meet the proposed new ocean drilling with a riser system, and appreciates the initiative of Science and Technology Agency of Japan and JAMSTEC to construct a new drilling vessel with riser capabilities. It strongly recommends that relevant Japanese Authorities take the necessary steps to begin to operate this new vessel before the envisioned end of ODP Phase III (1 October 2003).

6) CONCORD fully endorses an internationally managed and funded two-ship program along the lines of the 1996 ODP Long Range Plan. International scientific planning for riser-type drilling should begin as soon as possible under the guidance of an appropriate advisory committee.

7) CONCORD recognizes that further technological development in coring systems and borehole measurements is required for ODP Phase III. Considering that these are also essential elements in the proposed riser vessel operation, CONCORD strongly recommends that possible ways and means to cooperate with ODP in the development of these technologies should be pursued. In developing the final design and construction of the OD-21 drillship, and its drilling and riser systems, JAMSTEC should be prepared to work cooperatively with one or more of the world's leaders in commercial deepwater drilling technology.

CONCORD further emphasizes that:

Development of riser capability drilling within a future two-ship Integrated Ocean Drilling Program (IODP) must be seen as one of the most important elements in the ongoing preparations by the Earth science community to meet the scientific needs and challenges within the next century. Presently, our community is organizing its science into process-oriented and global experiments drawing on large facilities such as global seismic networks, deep continental drilling and ocean drilling. CONCORD envisages that the requested riser-drilling facility can only be realized through the combined resources of the world's leading nations in ocean sciences, and in collaboration with industry.

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Working Group 1 Report
Climate, Sea-Level Change, and Deep Biosphere

Executive Summary

Working Group 1 has designated the **Deep Sub-sea Biosphere: Exploring the Lost World** as the highest priority theme for early drilling by a riser-equipped vessel such as OD21. Understanding the origin and extent of the deep sub-sea biosphere has the potential to make significant breakthroughs in the fields of biotechnology, resource exploration, resource development and extraction, and in our understanding of climate change. Furthermore, the ability to piggy-back the deep biosphere experiments onto other themes early in the OD21 makes the deep biosphere an even more attractive and timely target. Important **Gas Hydrate and Associated Sub-Hydrate (Free Gas) Targets** are also possible within the same program in the areas hitherto impossible to drill for safety reasons.

An array of other important experiments requiring riser drilling is also discussed in this chapter. The significance of **Understanding the Initiation and Evolution of the Monsoon Climate System** that effects close to two-thirds of the world's population cannot be underestimated. A well-placed site in the South China Sea could significantly increase our knowledge of the interplay of tectonic processes and the development of the monsoon.

Working Group 1 Report

Exploring the Base of the Deep Sub-sea Biosphere

Background:

One of the fundamental, unanswered questions facing Earth scientists today is the nature of the Earth's deep, sub-sea floor biosphere. Microbial populations in deep sediments and rocks are estimated to represent greater than 10% of the carbon in the surface biosphere. Existing data demonstrate that significant microbial populations occur to at least 500 meters below sea floor (mbsf) (Figure 1). However, the extent of the deep sub-sea floor biosphere and the nature of these "extremophiles" are essentially unexplored. To determine the temperature, depth and age limits of this biosphere demands deep (>4 km) penetration , and thus requires riser drilling.

The results will have important societal implications for new biotechnology applications, for better predictions of the timing and character of the generation, alteration and extraction of hydrocarbons, for better predictions of the location and timing of the generation, concentration, and precipitation of metals during the formation of world class ore deposits, for defining key components of the global carbon cycle, and for understanding the origins of life on Earth and potentially elsewhere.

Questions relating to Microbial Ecosystems in Sediments

(1) *What is the extent of the deep biosphere biomass? What physical and chemical factors control the transition between the abiotic and biotic world?*

Microbes have been shown to exist 500 mbsf (Parkes et al., 1994). Existing theory predicts that the upper temperature limit of life is 120-130°C. Deep drilling will determine where the boundary between the biogenic and abiotic worlds actually occurs. Holes penetrating to and beyond this geotherm in selected settings, which include both deep sedimentary sequences (the transition to high temperatures can be studied long-term) and hydrothermal systems (in rocks and sediments where shorter-lived high temperature phenomena occur) will define the validity of the temperature control model. However, other environmental conditions, such as sediment type, lateral fluid flow, substrate availability, etc. may also affect the limits of life in the deep biosphere and need to be evaluated at the same time.

Establishing the energy source that fuels the deep biosphere is a major issue. Currently, the primary electron acceptors and donors in the deep biosphere are unknown. One potential source of energy for this microbial ecosystem is coupled with surface fertility; conversely, the biosphere in the deep oceanic lithosphere is potentially decoupled from surface processes, and thus exists independently from sunlight-based energy. Substrate quality may improve with depth because of increasing temperatures and may supplement the food source available to the deep biosphere ecosystem.

(2) *How diverse is the deep biosphere?*

The species composition and ecological structure of the deep biosphere ecosystem are completely unknown. Some of these forms may be novel organisms unique to the deep biosphere. The microbial assemblage may include forms that are the direct offspring of their entombed ancestors, perhaps modified by the evolutionary pressures of their evolving environment. Conversely, the assemblage may represent newly-arrived, opportunistic immigrants.

(3) *What is the impact of the deep biosphere on geological processes? How active are deep sedimentary microbes? What controls their activity?*

Microbes have the potential to mediate many important processes in sedimentary diagenesis, including the removal of seawater electron acceptors, the formation of authigenic pyrites and other minerals, and most especially the oxidation of buried organic carbon. There is currently some debate in the organic geochemistry community over the role of microbes, organic carbon/mineral surface area ratios, and oxygen in preservation of organic carbon (e.g., Keil & Hedges, 1995). The activity of microbes and how this activity is modified by other chemical and physical variables will be important in understanding diagenetic processes.

Experiment design – Deep subsea sediments

Exploring the deep sub-seafloor biosphere will require specific sites to study microbial stratigraphy in deep, old strata crossing the biotic/abiotic boundary (Figure 2). To achieve the desired thermal regime in areas where old sediments with complete successional zonations are developed will require drilling beyond the predicted geotherm (120-130°C). Thus, a normal gradient for old crust (~30 °C/km) will require holes in excess of 4 km. In addition to sampling the oldest microbial-bearing sediments, a primary target will be in an area with a thick sedimentary sequence that contains gas hydrates. Drilling through a major gas hydrate zone will assure that a significant microbial gas source lies below (Leg 164). There will also be potential microbial targets-of-opportunity in other deep holes and in hydrothermal systems.

To assess microbial activity, substrates or chemicals of interest will be placed in boreholes, incubated for a period of weeks to years, recovered, and analyzed. Compounds of interest could be included in tracer quantities (likely necessitating use of radioisotope-labeled compounds) to measure natural rates, or larger quantities to stimulate microbial growth. Possible substrates include labile organic intermediates such as acetate and amino acids and more refractory compounds, including natural organic matter extracted from the horizons of interest. Addition of inorganic compounds can test for utilization of various electron donors and acceptors. Abiotic controls must be conducted alongside these experiments to insure that measured changes are the result of microbiological activity.

These experiments could be deployed in the proposed multi-packer string and would directly communicate with the formation through ports in the instrumented casing. However, if fluid circulation in the layer is very sluggish, contamination may still present a problem; it may be more desirable to emplace experiments in the borehole wall through sidewall drilling. Complementary measurements (e.g. temperature, fluid chemistry, volatile concentrations, fluid advection) are also essential if the microbiological measurements are to be correctly interpreted.

Questions relating to Microbial Ecosystems in Oceanic Crust

(1) Do sub sea-floor microorganisms exist, and if so what types?

Microbes have been detected in drill cores from Hole 896A (Thorseth et al., 1995, Chemical Geology), but their widespread existence has not yet been established. The identities of these crustal microbes are also unknown, though many of them may represent novel classes, as rocky habitats have not yet been scrutinized by microbiologists.

(2) What carbon and energy sources do they utilize? How important are microbial processes in the alteration of oceanic crust?

Microbes from the lithosphere may derive their energy from organic carbon delivered to the subsea; alternatively, they may survive on magmatic volatiles or chemicals derived from crustal fluids or minerals. Such microbes could be the basis for a truly chemoautotrophic ecosystem, similar to the Columbia River Basalt SLiMEs (Subsurface Lithoautotrophic Microbial Ecosystems) of Stevens & McKinley (1995, Nature). Microbially-mediated inorganic reactions might have implications for the mechanism of some crustal alteration processes (Fisk, 1995?), as well as application to exobiological studies.

Experimental design

If microorganisms are at the fluid/rock interface, they may be extremely difficult to sample in recovered cores. Another chance to capture these microbes exists when sampling fluids in the borehole following drilling. It is imperative that the sample be uncontaminated with drilling fluids or seawater. Thus, fluid sampling in a multi-packer string with seated, sealed ports may present the most effective means of sampling the subseafloor biosphere in hard-rock environments. Horizons that produce fluid should be chosen for sampling, and the sampler should be adequately flushed.

In situ colonization experiments and enrichments will show what types of microbes inhabit different zones of the crust. Mineral surfaces of different textures and compositions, as well as chemical substrates (electron donors and acceptors) placed in incubation chambers mated to ports in the instrument casing wall, would selectively grow different classes of microbes for later analysis and identification by DNA sequencing. The colonization substrates can also be analyzed for evidence of microbiologically-mediated chemical or physical modification, though the appropriate abiotic controls would need to be similarly treated.

These experiments will be deployed within multi-packer instrument strings and must be recovered (after weeks or years) and analyzed on shore. The experiments must be accompanied by measurement of complementary hydrogeological properties to place the microbiology in the proper context.

Chance of breakthrough:

Current ignorance about the base of the deep biosphere assures that any exploration of this frontier will result in significant scientific advancements. The chance of a significant breakthrough for the resource industries is high. Understanding of the extent and nature of the deep biosphere should help to design experiments to determine extent of extraterrestrial life.

Technological Requirements:

Contamination tracers, accurate downhole temperature measurement tools, *in situ* fluid and gas samplers, multi-packer strings, *in situ* microbial borehole experiments, and remote samplers will need to be developed. Industrial collaboration is essential to develop new geochemical tools, such as microprobes coupled with DNA chips and novel biomarkers.

Infrastructure Requirements:

A permanent, well-equipped, on-board microbiology laboratory with anaerobic chambers is essential to allow handling and culturing of these microbes under *in situ* conditions. Provisions must also be made for immediate post-recovery radio-isotope tracer work.

Collaboration Required:

The similarity of the aims of the deep sub-seafloor biosphere research to exobiology pursuits demands that a meaningful dialogue be developed between sub-seafloor and space agency scientists and engineers (e.g., NASA, NASDA, ESA) who are trying to develop new technologies to address extraterrestrial research. Perhaps more importantly, is the tie to the continental drilling community who have already been investigating the extent of the biosphere below the land surface.

The Extent and Nature of Gas Hydrates and Free Gas

Background:

Hydrate is an ice-like solid compound composed of water and low-molecular-weight gases (predominantly methane) which form under conditions of low T, high P and adequate gas concentration. Gas hydrates within marine sediments are detected by characteristic bottom-simulating reflectors(BSR) in seismic profiles (Figure 2).

The amount of solid gas hydrate is thought to be comparable to the total amount of fossil fuels (~10,000Gt C) based on the wide distribution of BSR's in the continental slope and rise sediments. However, we still have very little documentation about the occurrence and exact amount of gases stored as solid gas hydrates. ODP Leg164 has revealed extensive distribution of free gas zone beneath BSR, but the amount of free gas in this reservoir is entirely unresolved.

Destabilization of marine gas hydrate is suspected to be a trigger of slope failure that generate giant slides on the continental margin, which in turn may cause a global warming through the release of enormous amount of greenhouse gas methane into the atmosphere-ocean (Figure 3). However, the connections between gas hydrate/free gas, giant slides, and climatic change have not been verified. Gas hydrate is also attracting growing interest as a natural gas resource.

Questions to be addressed:

The objectives of riser drilling of marine gas hydrate and free gas bearing sediments are to,

1. determine the source of gas for the formation of solid gas hydrate and gas bubbles below, in particular, in terms of genetic connection with bacterial gas production in the deep biosphere,
2. delineate the migration paths of methane and establishment of the formation process of free gas and gas hydrate zone,
3. establish the total amount of free gas and gas hydrate, and
4. determine the location and nature of paleo gas hydrate zones (PGHS)

Chance of Breakthrough:

As a huge carbon sink in the shallow geosphere, gas hydrate may play an important role in changing global climate, earth surface environments, and evolution of biosphere. Determination of global inventory of marine gas hydrate and associated free gas would constitute a significant advance in our understanding of the global carbon cycle.

Experiment design:

Riser drilling is an essential component of a much larger experiment to understand the distribution and volume of hydrates and free gas trapped below. There are significant opportunities to couple the gas hydrate/free gas experiments with deep biosphere experiments. The experiments outlined below could piggy-back with a number of programs in a variety of settings.

- Riserless drilling down to ~500 mbsf through gas hydrate zone followed by riser drilling of free gas zone beneath BSR down through the deep biosphere (> 4 km

below sea floor).
- In deep water riser drilling may be applied for gas hydrate zone. Under the water depth of ~ 4,000 m, the base of gas hydrate stability occurs at depth of ~600 m below seafloor (Figure 4).
- Need to drill through the depth of minimum solubility of methane (~1.5 kmbsf) to establish the relation between solubility change and the formation of methane bubbles. Methane solubility changes with increasing depth is suspected to be connected with the generation of gas bubbles and formation of free gas charged zone.
- High resolution in-situ sampling of the pore waters to determine the chemistry and isotopic characteristics.

Possible sites include

1. Nankai Accretionary Prism - transect drilling from shallow water (~1,000 m) to deep sites (~3,000 m). Generation, migration, and accumulation process of gases and development of gas hydrate zone will be studied in connection with fluid migration within the accretionary prism and generation of biogenic gas at greater depths (deep-biosphere).
2. Southeastern continental margin of US - deep water drilling (>4,000 m) at the foot of Blake Ridge would provide chance to drill gas hydrate zone by riser system.
3. Makran Fold Zone in Oman Sea- transect drilling of this "classic" area with strong BSR within deformed sedimented ridge will provide important and essential information to establish the model of gas and hydrate accumulation in the course of accretion of pelagic and hemipelagic sediments.

Technological requirements:

1. Improvement of better gas sampling methods, e.g., Pressure Core Sampler, Mud Monitoring System during riser drilling, etc., is essential.
2. Developing riser drilling technology at shallower subbottom depth (< 300m ?) is highly desirable.

Collaboration required:

- Collaboration with microbiology group is essential.
- Collaboration with oil and gas industry.
- Collaboration with accretion tectonics group when drilling in Nankai Trough.

The Uplift of Tibet/Himalayas and Initiation of the Monsoon

Background

The collision of India with Asia over the past 60 million years has resulted in an uplifted region of exceptional extent (equaling half that of the United States) and elevation (averaging 5 km for the Tibetan Plateau and higher for the Himalayas). The topographic effect of the plateau has resulted in the development of a monsoon climate over much of Asia and Africa, where close to two-thirds of the world's population lives (Figure 5). Paleo-monsoons possibly played significant roles in influencing the evolution of human ancestors and the development of ancient cultures.

The rise of the Tibet/Himalayas system has affected at least two major controlling factors of the global climate:

- A decrease in atmospheric CO_2 concentration, through the enhanced terrestrial weathering of silicate rocks; and
- Changes of atmospheric circulation and heat transfer due to the high topography of the plateau.

New data suggest that the eastern part of the Tibetan Plateau began its rapid rise about 40 Ma (Chung et al., in press), while the western part rose around 20 Ma (Harrison et al., 1992). This diachronous uplift might have triggered the early Oligocene (36 Ma) glaciation of Antarctica and initiated the monsoonal climate in the Neogene.

Drilling Indian Ocean sediments during ODP has provided valuable records of the close relationship between the evolution of the monsoonal climate in south Asia/east Africa and the uplift of the Himalayas and Tibetan Plateau. Yet, due to the heretofore limited access to the older part of the sedimentary record and a lack of drilling in the marginal seas east of the plateau (west Pacific), little is known about the earlier part of monsoon history or the evolution of the east Asia monsoon (Figure 6). When did it initiate, and has the character of the monsoon changed through time? Riser drilling of the Bengal Fan in the northern Indian Ocean and of the thick sediments filling the South China Sea is a key to unraveling the dynamics of this interaction of tectonics and climatic processes during a major part of the Cenozoic.

Key Questions

1. When and how did the monsoonal climate initiate?
2. What is the relationship between monsoon development and the Himalayas/Tibetan Plateau uplift?
3. When did erosion of the Tibetan Plateau cause extensive weathering and draw down of the atmospheric CO_2?
4. Was the draw down in atmospheric CO_2 a trigger for Oligocene (~36 Ma) global cooling?
5. How did the tectonic development and the resulting monsoon climate affect biotic evolution, extinction and migration, especially hominid evolution and dispersal?

Chance of Breakthrough

By drilling deep holes in strategically located land-ocean linkage points in the marginal seas and abyssal fans of the northern Indian Ocean and off South-East Asia, we can understand the progressive development of the largest tectonic uplift of the Cenozoic and its influence on global climate. Riser drilling promises to reveal the as yet unknown history locked in the deep, thick sediment layers left by erosion of the Tibetan Plateau and Himalayas, by allowing access to drilling targets specific to the questions listed above: deep sections of continental margins, basal parts of deep-sea fans, and potentially hazardous, hydrocarbon-prone environments.

Experimental Design

Phase I -- Drilling in the South China Sea

Targets are high resolution, undisturbed hemipelagic records from rapid sedimentation rate areas near the continental margin. Riser technology is required because of the large potential for hydrocarbons and the unstable condition of coarse sediments in buried rift basins. Optimum sites are in marginal seas in the western Pacific (e.g., northwestern South China Sea), at outer-shelf to upper slope sites (i.e., 500-1,000 m water depths), and with penetrations up to 4,000 m below sea floor in order to reach the late Paleogene.

Phase II -- Drilling of the Bengal Fan, Indian Ocean

Targets are in areas where the eroded sediments of the Tibet/Himalayas are preserved, e.g., the distal side of the Middle Bengal Fan. Water depth is about 4,000 m, with a desired penetration to 6,000 m in sediments.

Technological Requirements

1. Safety measures to deal with potential hydrocarbon hazards.
2. Retrieving deep sections up to 6,000 m below seafloor.
3. Maintain stable hole conditions and obtain better core recovery of potentially unstable sequences, such as unconsolidated fan sands.
4. Desirable *in situ* integration of logging data with examination of cuttings from deeper sections where core recovery may be poor.

Collaboration Required

- Cooperation with gas/oil industry
- Collaboration with continental drilling programs
- Collaboration with *JOIDES Resolution* legs in other key areas
- Collaboration with PAGES, IMAGES, MESH, and SCORE of the UN.

A Mesozoic Reference Section: Anchoring the Global Array

Background

A long-standing goal of scientific ocean drilling has been to obtain records of global change that span the early history of Mesozoic sedimentation in the world's oceans. Such records are necessary to understand the relative stability of greenhouse and icehouse worlds, and the effects of the Wilson Cycle on the evolution of the ocean and atmosphere. Very little is known of the behavior or influence of the Mesozoic deep ocean.

A great deal is known from the Alpine-Himalayan Tethyan belt from on-land geological research and from industry exploration, yet this research has no anchor or reference sequence in the deep ocean. These on-land studies provide local/regional insights into disconnected parts of the column. Deep drilling would provide a key reference section that would extend our knowledge of the Mesozoic and place the regional studies in a global context. Such a reference section would serve a large community of earth scientists studying the Mesozoic.

Key Questions

What are the fundamental mechanisms that drive climate and oceanic variability on long timescales?

What climatic process dominated, and what mechanism sustained the extremely warm Greenhouse Earth?

What process or event terminated the Greenhouse climate pattern? Was it the cessation of the global circum-equatorial circulation (ocean linkages/ gateways)?

What were the dominant frequencies of Milankovitch forcing during the Greenhouse?

How did biogeochemical cycles operate and vary during the Mesozoic?
What effect did evolution/radiations have on carbonate cycling?
How did the locus of carbonate cycling and budgets vary between continental shelves and the open ocean?
How did the CCD vary during the Mesozoic (ocean alkalinity)?
What was the balance between oceanic and continental chemical fluxes?
What was the history of paleo-oxygenation (including black shales)?

Chance of Breakthrough

By retrieving continuous geologic/climatic records from the Pacific and Indian Oceans that were hitherto unobtainable, we will be able to fill in a major gap in the global array – the deep ocean. Increased hole stability and deeper drilling (>3,000 m) provided by the riser drilling will ensure the recovery of continuous long geologic/climatic record down to Jurassic in the Pacific and Indian Oceans. Most Mesozoic climatic/oceanic records obtained up to now are from the Atlantic where Cenozoic sedimentary cover is relatively thin. During the Mesozoic, however, the Atlantic Ocean was a relatively narrow seaway, and today's oceanographic conditions must be quite different from the Pacific-Tethys realm that dominated the Mesozoic aquatic world.

Experimental Design

Recover a deep Mesozoic pelagic reference section (>2,500 m continuous core, 100-180 million years) on ocean crust to serve as an anchor for existing and developing global array of sections including:

- transgressive shelf sequences recovered by industry/DSDP/ODP:
- obducted pelagic sequences from the Alpine-Himalayan Tethyan belt;
- shallower, less complete oceanic Mesozoic sequences recovered by
- DSDP/ODP as part of an integrated two platform experiment

A possible location for a deep riser hole has the following characteristics

- *Geographical area:* Western Somali Basin (Figures 7).
- *Water depth range:* 3,500 to 5,000 m.
- *Penetration depth range:* 2,500 to 3,500 m (Figure 8).
- *Borehole temperature estimates:* normal or lower geothermal gradient.
- *Possibility of hydrocarbon occurrence and its estimated volume/origin/setting:*
  - zero in upper 1,200 m of section (DSDP 241);
  - slim in deeper section (stratigraphy appears continuous to upslope regions).
- *Degree of contamination of cores which would be acceptable (i.e., magnetics):;* none (magnetics is critical).
- *Estimation of lithologies and thicknesses in borehole sequence:*
  - deep-sea carbonate oozes and claystones - upper 1,200 m.
  - hemipelagics, carbonates, claystones - lower ~2,000 m.
- *Historical data on borehole stability?*
  - upper 1,200 m highly stable (single-bit DSDP Leg 25 hole).
  - *Historical data on core recovery:* low (spot coring at Site 241).
  - *Historical data on hydrocarbons:* none in upper 1,200 m (and none found yet on conjugate Somali/Kenya and Madagascar margins).

Technological Requirements

Deep hole stability
High resolution down-hole logging (including FMS and GLT)
Comprehensive multi-sensor track
Access to shore-based split-core

Infrastructure Requirements

Regional geology and extensive site survey, especially enhanced MCS surveys

Collaboration Required

Deep biosphere researchers
Physical and chemical processes in thick sedimentary packages – *whom do we collaborate with?*
MESH (extreme climates)
Climate modeling community
Petroleum exploration industry
National Geological Surveys

Sea-level Rhythms and Responses in the Greenhouse World

Background

The JOIDES Resolution has successfully addressed a number of Neogene sea level objectives: sea level amplitude and timing can be extracted from the sedimentary architecture and the stable isotope proxy, at times when the primary forcing function appears to be the waxing and waning of continental glaciers.

However, a major question has not yet been addressed. What is the mechanism for sea-level oscillations during periods where significant volumes of continental ice appear to be absent? Neogene and Cretaceous stratal geometries appear to be same and have been used to suggest that the same mechanism for sea-level oscillations is active in both periods. Why are they the same? Can similar stratal geometries be produced by sea-level oscillations of different magnitude in areas of similar tectonic subsidence rates?

Multiple legs have already been drilled:

- Leg 166, Bahamas, produced good quality dates for specific sequence boundaries,
- Leg 174A, New Jersey Mid-Atlantic Transect on the continental shelf, produced lower resolution dates but achieved its objectives when combined with the results of Legs 150, 150x, and 174Ax
- Legs 143/144, Atolls and Guyots, did not achieve its sea level objectives

So far, sea level experiments have concentrated on:

- Old passive margins and carbonate platforms on cool crustal foundations chosen for their simple tectonic history (e.g., New Jersey, Bahamas).
- The utilization of transects, because the most complete record occurs in the thick sedimentary prisms of continental margins.
- Neogene sections, where stable isotope proxies for the timing and amplitude of sea level changes can be compared to sedimentary responses.

Experimental design for ice-free periods, such as the climatic extreme during the Cretaceous, must take into account the lack of climate and/or sea level proxies but is otherwise similar to the Neogene.

Societal Relevance

A key output for this experiment is a better calibrated and physical stratigraphic framework for the Cretaceous for use by the resource exploration industries. In addition, the results from drilling deeper previously unreachable Cretaceous sections will play a significant role in defining the baseline attributes of a period of extreme climate.

Questions

The objective is to search for and identify the processes that produce the globally observed cyclical stratigraphic response characteristic of the Cretaceous Greenhouse world. Riser drilling is a key component of sea level experiments on a number of Cretaceous margins. It offers the opportunity to anchor the age model for Cretaceous stratal surfaces essential to understanding the rates, magnitudes and effects of sea-level oscillations.

What are the links between eustasy and sedimentary architecture in an ice-free world?

Why is the sequence stratigraphic/geometric response of the Earth the same in both the "Icehouse" and "Greenhouse" worlds?

What is the degree of synchroneity of sequence boundaries in both time periods?

Can the physical and chronstratigraphic framework for the Cretaceous be improved significantly?

Chance for a breakthrough: "Cretaceous Clinoforms are Critical for Cyclicity"

The goal, to look for possible driving mechanisms (e.g., changes in spreading rates, LIPS emplacements) in the Greenhouse, can be reached if good drilling recovery in characteristic Cretaceous stratigraphic geometries is achieved and dating is optimized. Timing/dating sequence boundaries is the key. Whether or not the identified Greenhouse mechanisms are causal for the observed Cretaceous stratigraphic geometries, these mechanisms can then potentially be used to test the assumption that glacial-eustacy is the primary driving mechanism for similar Neogene stratigraphic geometries.

Experiment Design

Drilling Transects

- Multi-platform, on-land, alternate platforms (0-75 m), JOIDES Resolution (75-ca. 500 m), OD21 vessel (500 m and deeper)(Figure 9).
- Rationale - drilling and sampling clinoform geometries + associated lithologies; they do not carry the (Neogene) stable isotope record proxy for presumed sea level change, but can be used to infer timing (at least to inherent biostratigraphic limits) + paleowater depths.
- target - multiple margins/similar geologic settings in the Cretaceous, e.g., offshore Brazil (mixed carbonate/clastic), SW Africa (siliciclastic), NW Australia (primarily siliciclastic).

Technology Requirements

Prior to drilling:

- Extensive understanding of regional geology to high grade areas

- Extensive geophysics (at various frequencies) to define sequence stratigraphic geometries.

Drilling Approach:

- Some target depths may be large - riser will be needed, to ensure hole stability (beyond the needs of surface casing); however, JOIDES Resolution could be used to set up some of these riser holes.
- As we learn about hole stability, operational planning will evolve.
- The settings are clearly hydrocarbon-prone; BOP is advisable/required.
- Multiplatform emphasis, as defined above.
- For paleomagnetic studies, drilling-induced remnant magnetization should be avoided. Cores with azimuthal orientation will be required.
- Complete logging suites, including Vertical Seismic Profiles, and mud logging (LWD) for optimal geophysics/log correlations are required.

Infrastructure Requirements

No special infrastructure is required to pursue this initiative, but we must highlight the difficulty of finding and funding research vessels with capacity to undertake the necessary survey work well in advance of the final definition of targets. Utilization of petroleum exploration datasets for the study areas is essential.

Collaboration

Petroleum Industry

- as provider of geophysical and geological data of all kinds.
- as collaborator on studies of basinal stratigraphy, e.g., providing and interpreting downhole logs of adjacent commercial wells.

National and regional geological surveys

- for onland drilling support
- nearshore surveys
- logistical support
- government clearances

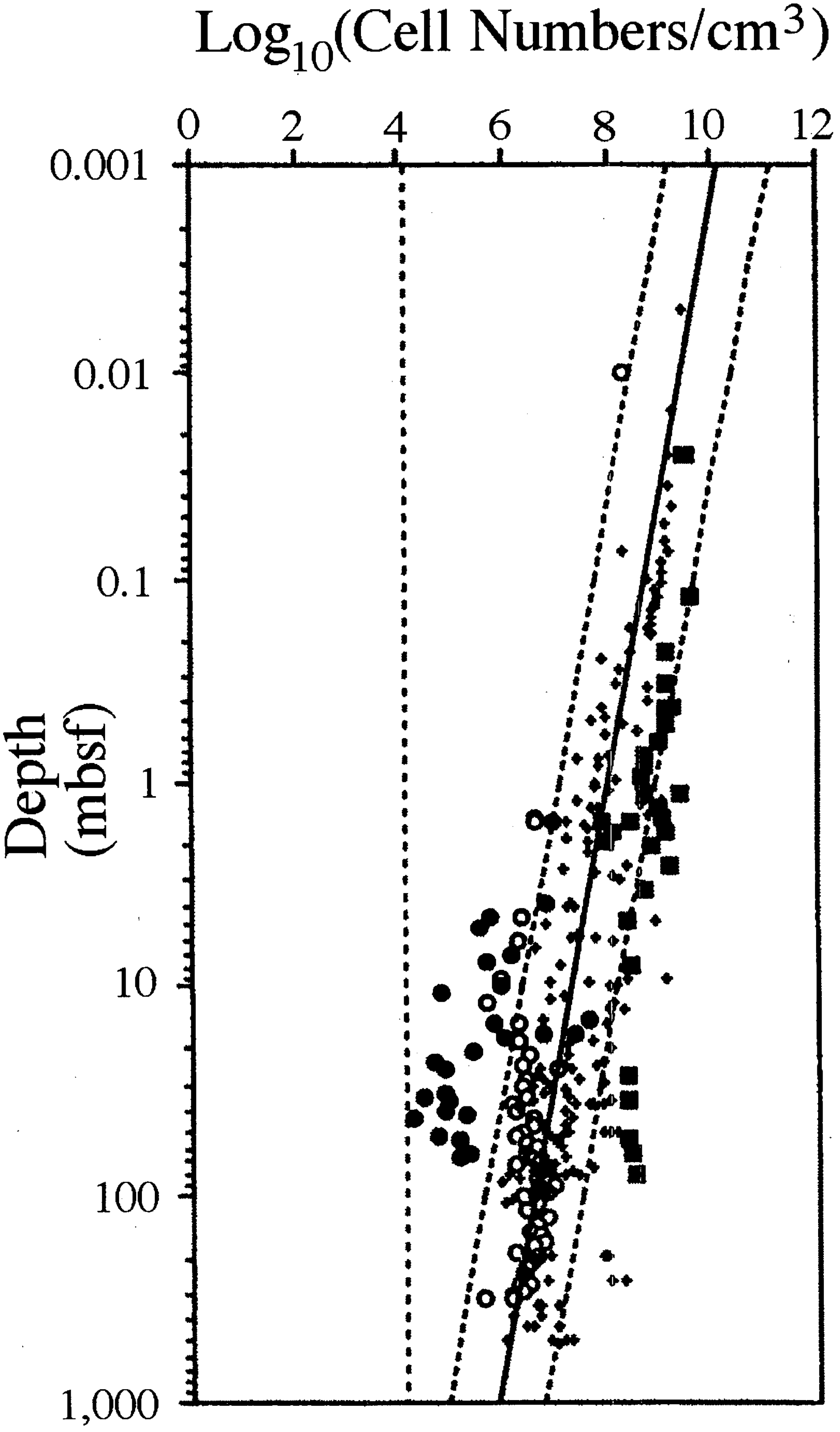


Figure 1: Depth distribution of total bacterial numbers found in oceanic sediments.
(Parkes et al., 1994)

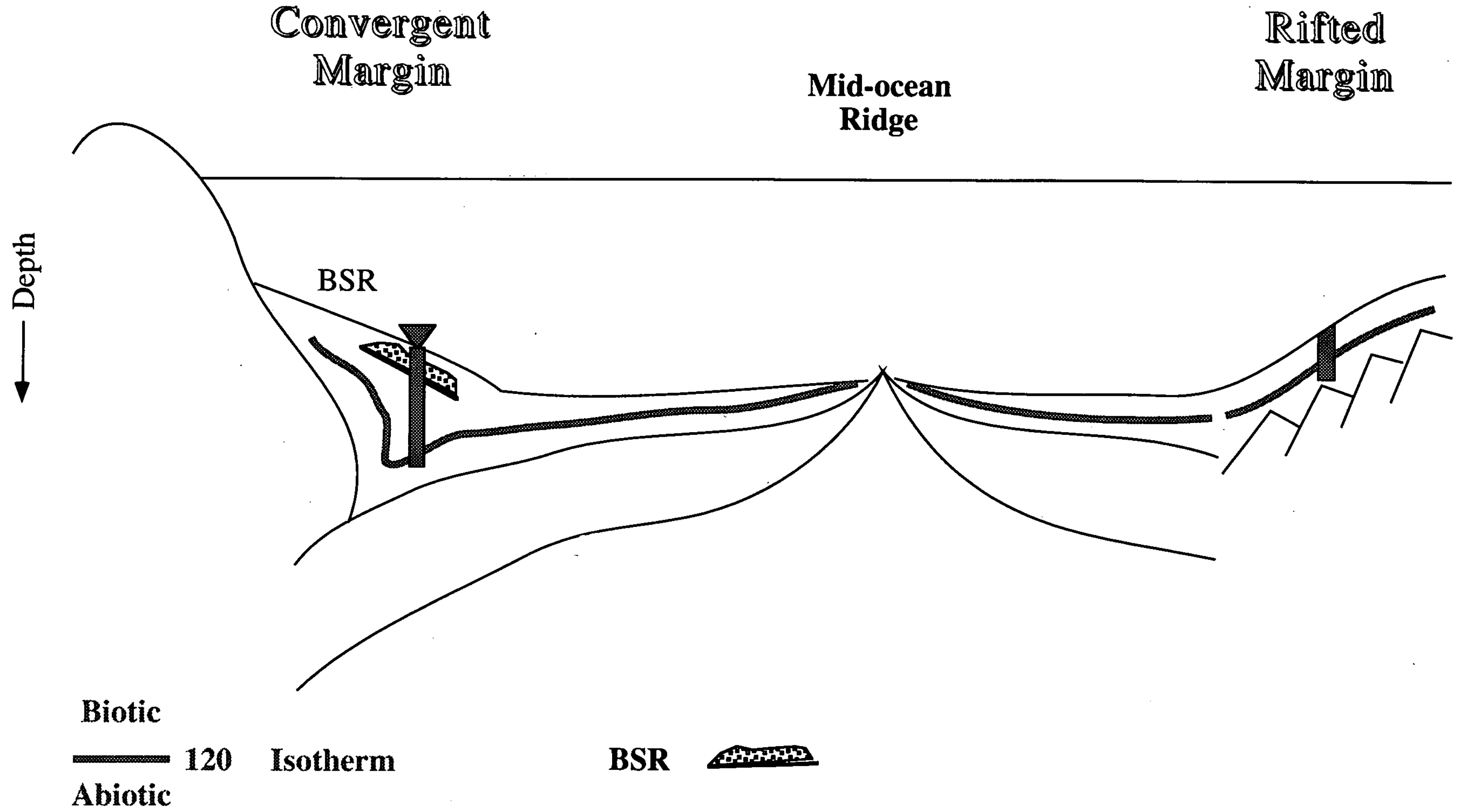


Figure 2: Schematic cross-section of an ocean basin from a convergent margin across a mid-ocean ridge to a rifted margin. Superimposed are the major crustal structural boundaries, as well as the 120 °C isotherm. This isotherm represents the predicted base of the deep sub-seafloor biosphere. Drill sites, as shown, need to be selected where the concentration of microbial products is significant, such as where there are bottom simulating reflectors (BSR). Riser drilling allows penetration of this isotherm and beyond to establish the actual limits of life in old and deeply buried oceanic sediments.

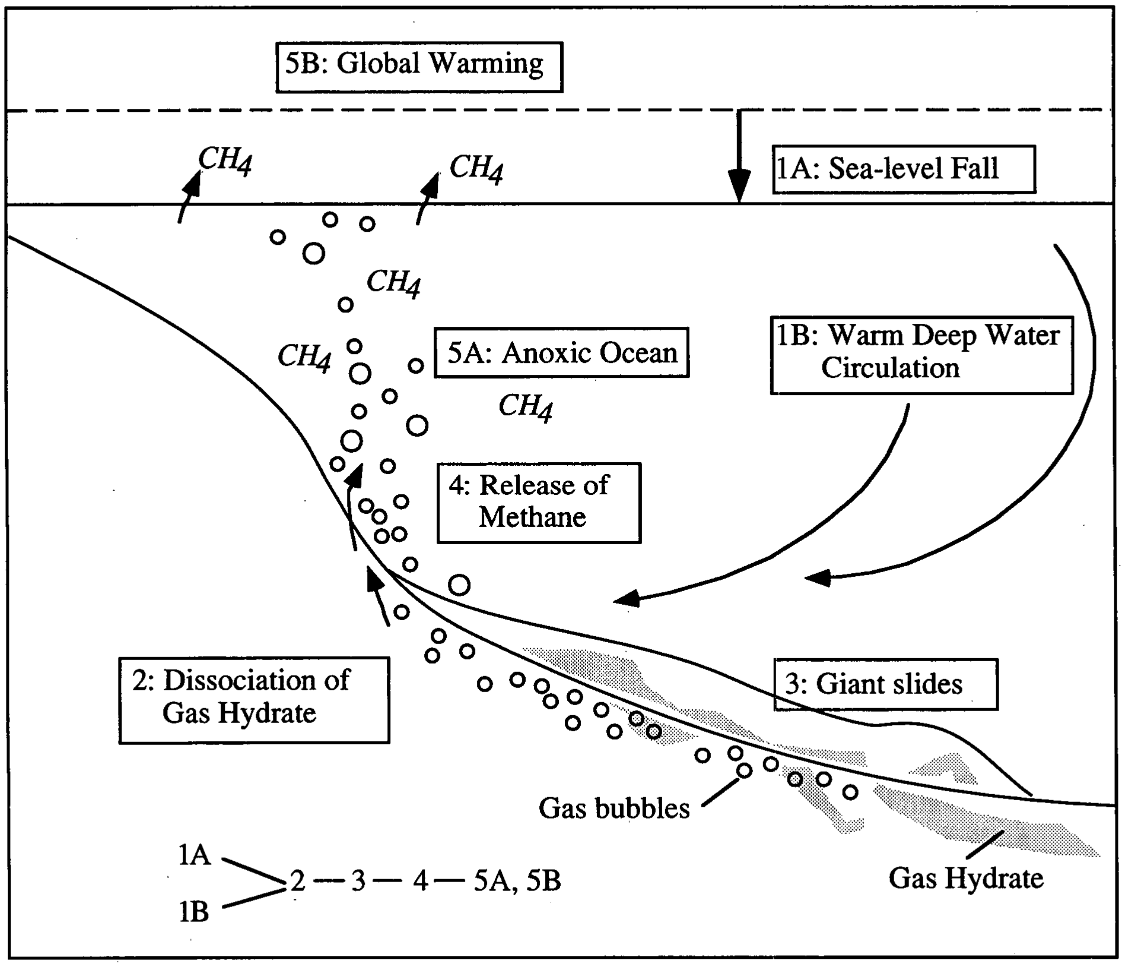


Figure 3. Connection among gas hydrate/free gas in shallow geosphere, slope instability, and environmental change with potential for global warming.

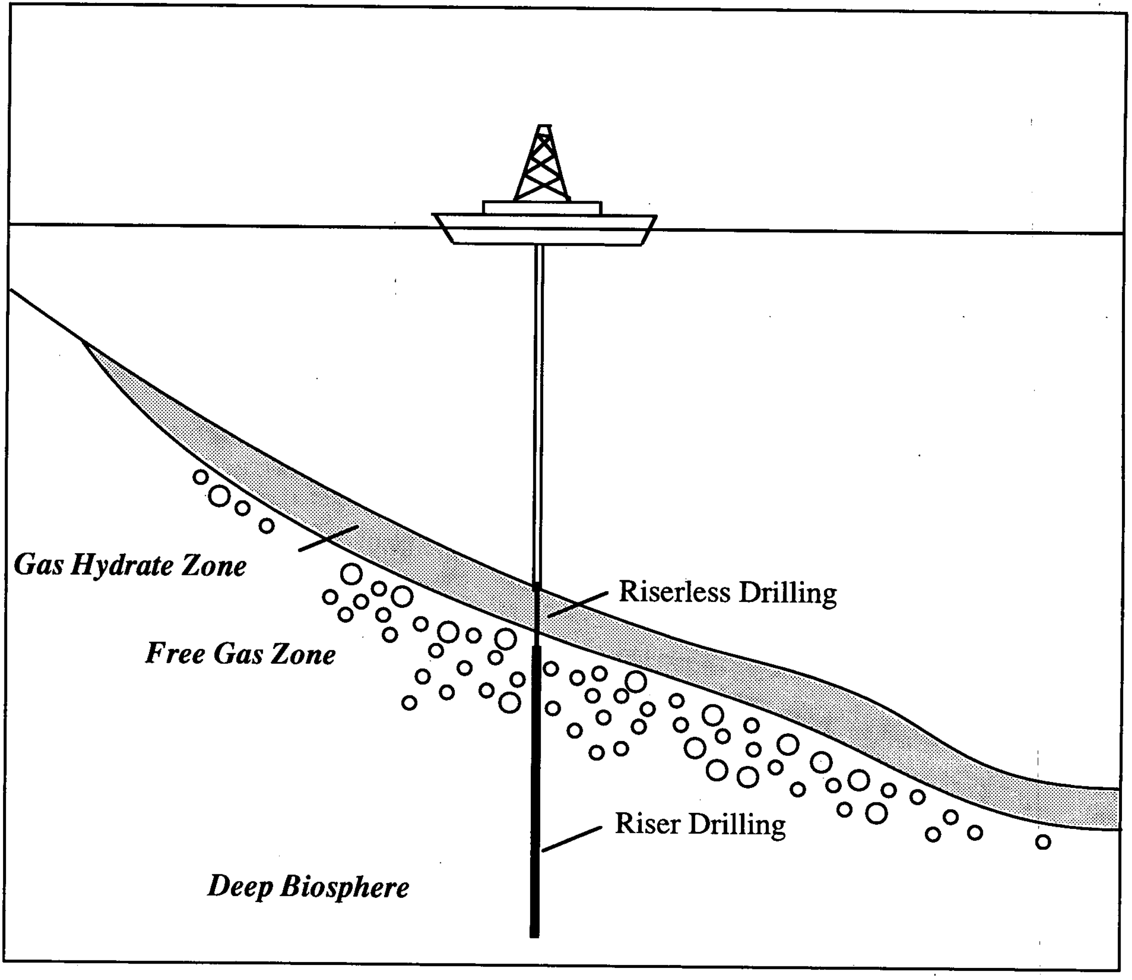


Figure 4. Design of deep drilling through gas hydrate zone (< ca. 400 mbsf), BSR (at around 400 mbsf), free gas zone (400 m ~ 600 m?), and deep- biosphere.

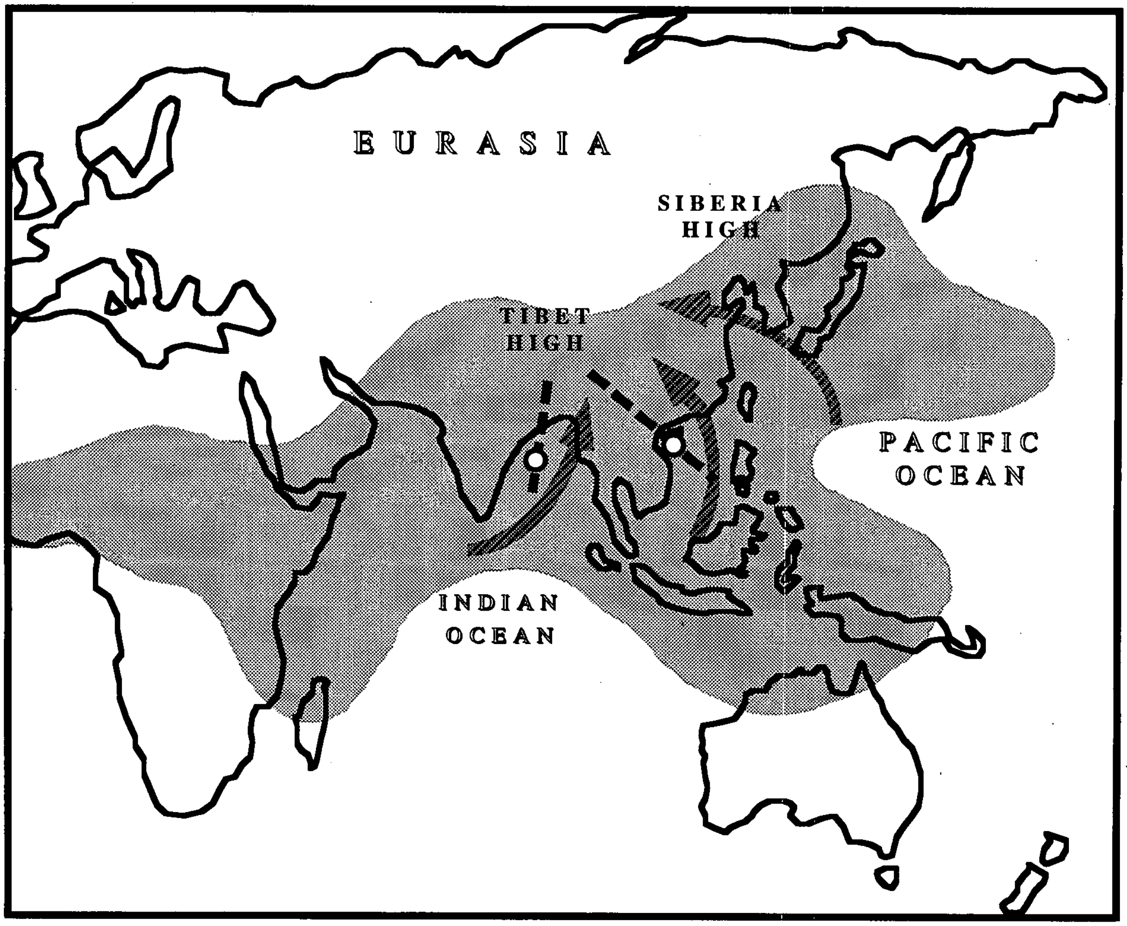


Figure 5. Geographical extent of the area affected by monsoon. Profiles and sites in the South China Sea and the Bengal Fan are shown by dots on thick brocken lines. Arrows indicated the summer monsoon wind direction.

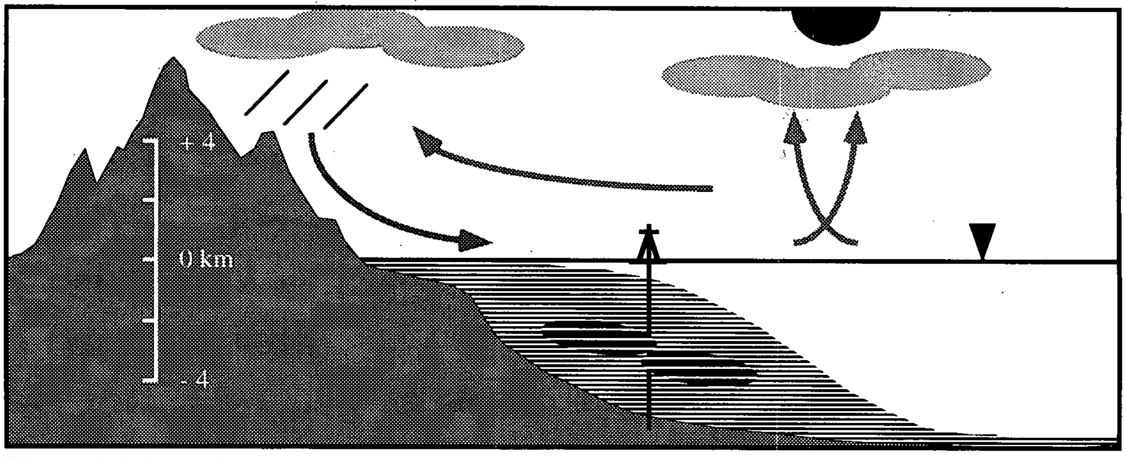


Figure 6. Schematic cross section of the thick sedimentary sequence (thin hatching) that record detailed history of the plateau uplifting and monsoon development. (see Figure 5 for profile locations). Thick hatching indicate the possible hydrocarbon burials. Arrows show the hydrological cycle of the summer monsoon: the upper arrow for the atmospheric moisture transport and the lower arrow for the river flow that carries eroded sediment.

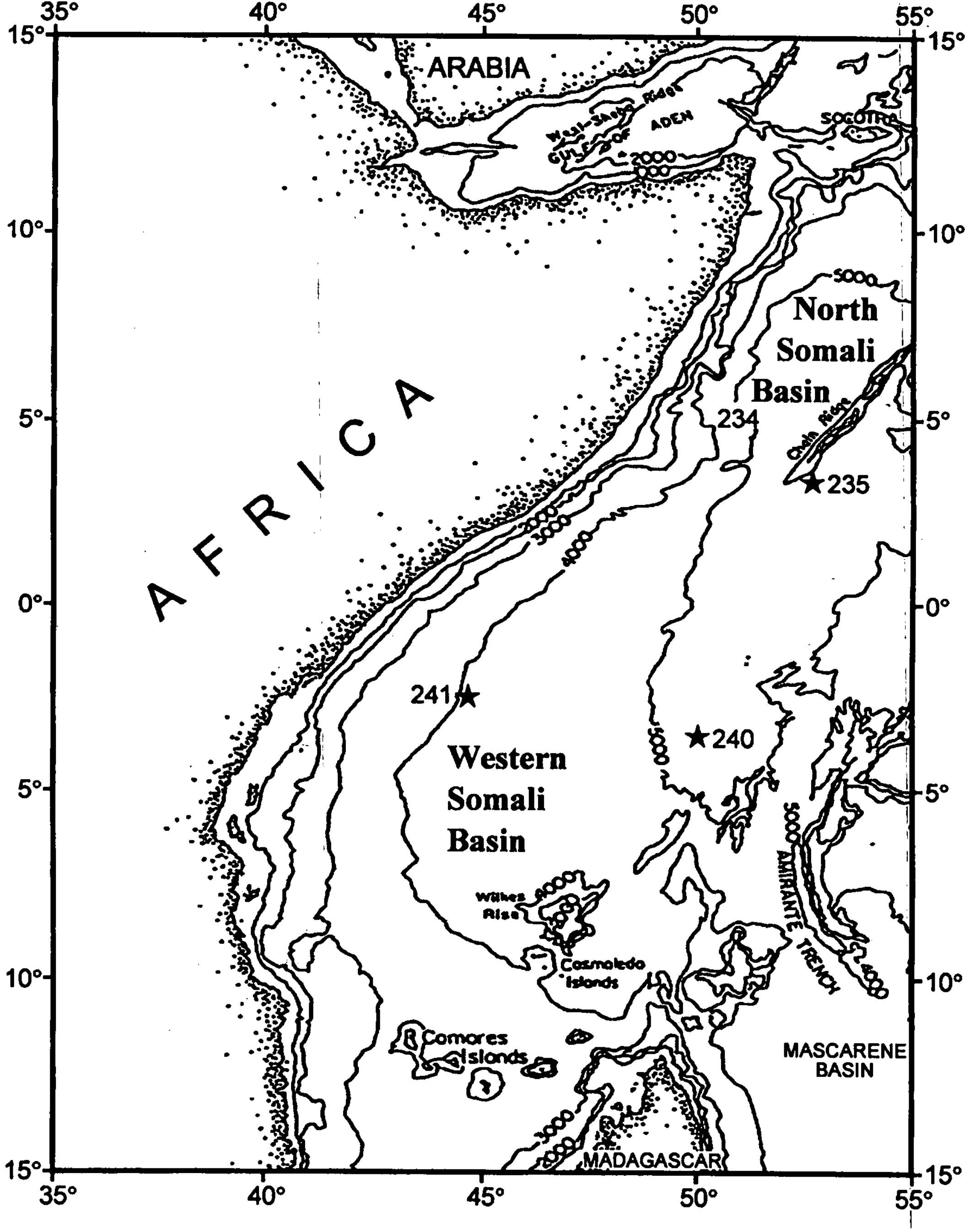


Figure 7. Bathymetric map of the western Indian Ocean and location of the Somali Basin.

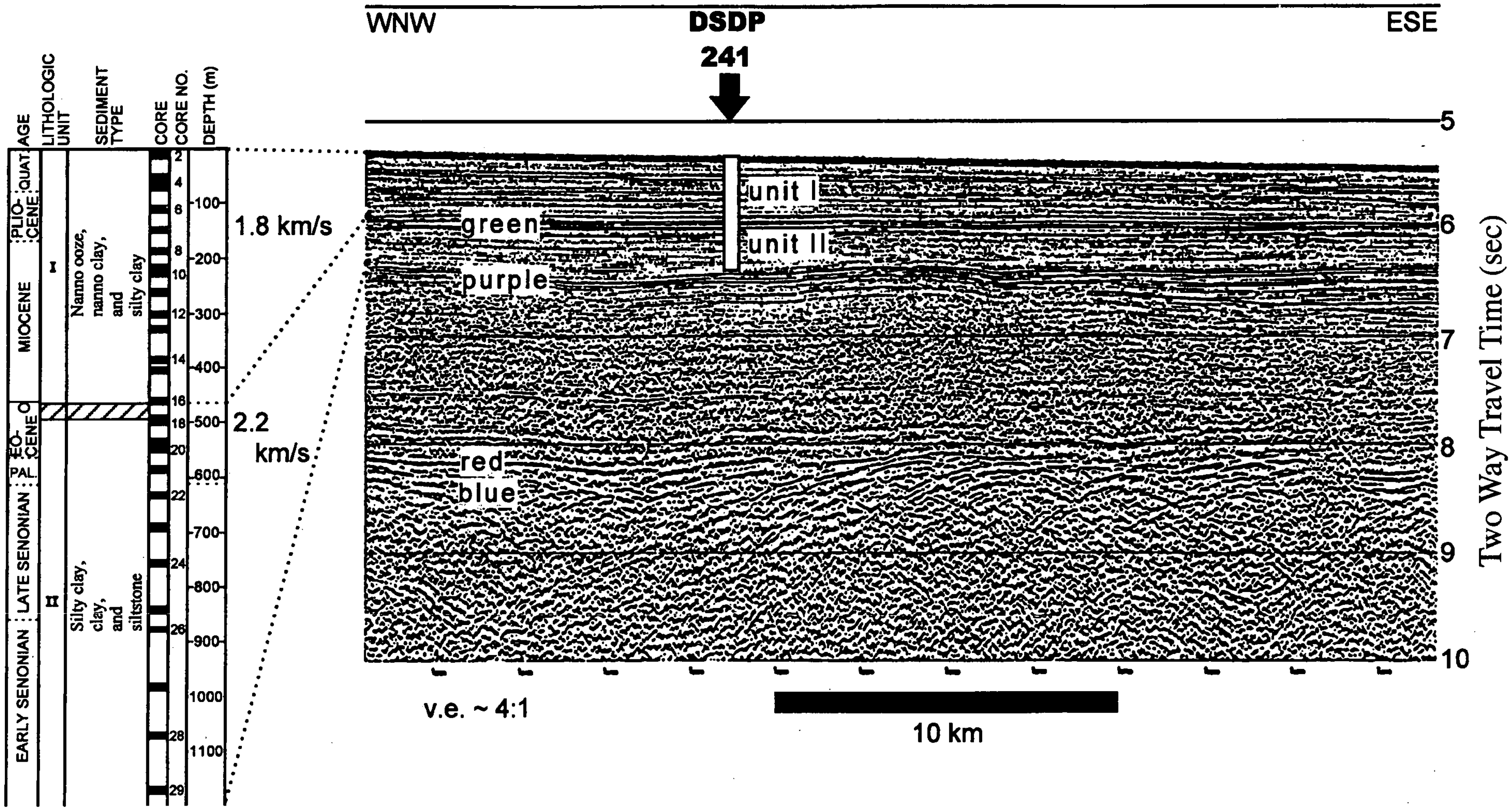


Figure 8. Seismic reflection profile illustrating potential target for a Mesozoic reference section (from Coffin, M.F., and Rabinowitz, P.D., 1988).

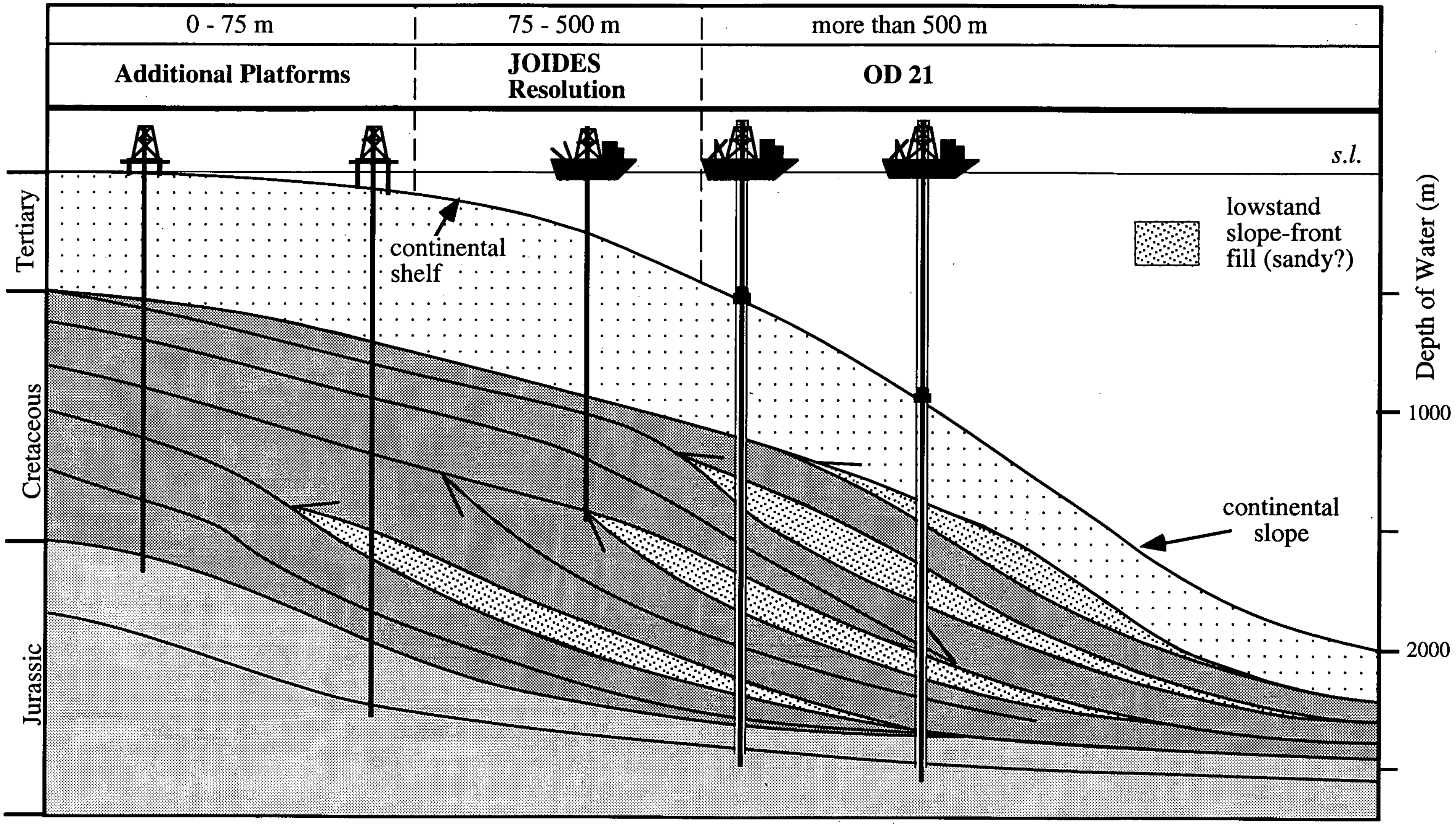


Figure 9. Schematic cross section of a succession of Cretaceous clinoforms beneath a continental margin, showing the multiple-drilling platform strategy required for their systematic sampling. The riser-equipped vessel, operating in water depths beneath the modern continental slope, will be critical for reaching the seaward edges of these stratigraphic systems, where they are deeply-buried.

Working Group 2 Report
Architecture of Ocean Lithosphere

Executive summary

Working Group 2 has designated **the 21st Century Mohole** as the highest priority for drilling. This would consist of a complete oceanic crustal section through the lower crust to the Moho in ocean lithosphere generated at a fast spreading ridge. This would address longstanding and fundamental questions, including the origin of the seismic Moho and the validity of the ophiolite models for lower oceanic crust and upper mantle. Since lithospheric accretion at fast spreading ridges is, to a first order, time and space independent, a single hole will provide a general knowledge of the deep structure of immense parts of the ocean floor. If ophiolites are good analogues to ocean lithosphere, integration of ophiolite and marine studies will revolutionize our understanding of ocean lithosphere formation.

Drilling through an upflow zone of an active hydrothermal system, as the second priority, to test the current models of heat transfer mechanisms between the heat source and circulating fluids, and will allow the definition of the water-rock reactions that ultimately result in the formation of massive sulfide deposits on the sea floor. Quantifying the elemental exchange between the lithosphere and hydrosphere during hydrothermal circulation is critical to understanding the role of water-rock reaction in regulating the chemistry of the ocean.

Riser drilling is critical for both of these objectives, as deep drilling in these environments requires hole stability and the ability to remove dense cuttings from the hole. The first objective requires the capability of drilling in water depths of 4,000 m or greater, since the hole should be located in a 30 my old lithosphere created at a fast to superfast ridge. This drilling operation would also address the question of the aging of the oceanic lithosphere which is related to the second priority. The second objective is attainable during the first phase of OD21 (2.5 km riser) either on a fast spreading ridge or in the backarc basins. It could also be used to test the feasibility of Moho drilling.

Introduction

The highest priority of WG2 is drilling through the lower crust to the Moho in an ocean lithosphere generated at a fast spreading ridge, "the 21st Century Mohole". Because at the first order lithosphere accretion at fast spreading ridges is time and space independent, a single hole should provide a general knowledge of the deep structure of immense parts of the ocean floor, which are presently unknown. It should also result in a better understanding of the accretion processes taking place at ridges. Thanks to these deep holes, breakthroughs are expected in two domains. Firstly, it will answer the question of whether the seismic Moho is a boundary between the mantle and basaltic crust or if it is an alteration (serpentinization) boundary within the mantle. In the latter case, accepted models and budgets of mantle melting below ridges and fluxes of ocean crust in subduction zones would have to be drastically revised. Secondly, drilling the Moho will allow to test the validity of the ophiolite model. If ophiolites are good analogues to ocean lithosphere, integration of ophiolite and marine studies will revolutionize our understanding of ocean lithosphere formation.

The second priority is drilling through an up-flow zone of an active hydrothermal system, in order to understand the functioning of this major mass and energy exchange system between solid and liquid Earth.

The oceanic crust represents the product of complex interactions between magmatic, hydrothermal and tectonic processes. Post-emplacement water-rock reactions during both hydrothermal alteration and low temperature weathering result in the transfer of mass and energy between the lithosphere and hydrosphere. These reactions play a role in regulating the chemistry of seawater and in the formation of massive sulfide deposits on the seafloor. In addition, these reactions influence the chemical composition of the oceanic crust and sediments which is recycled at subduction zones. However, the impact of the water-rock reactions on global geochemical mass balances has been the subject of considerable debate and needs to be quantified.

The second objective is attainable during the first phase of OD21 (2.5 km riser) either on a fast spreading ridge or in a backarc basin. It could also be used to test the feasibility of Moho drilling. The first objective requires the capability of drilling in water depths of 4,000 m or greater, since the hole should be located in a 30 my old lithosphere created at a fast to superfast ridge. This drilling operation would also address the question of the aging of the hydrothermal system which is related to the second priority.

Ultra Deep Drilling of the Lower Oceanic Crust and Moho

Background

Fossil ocean crust preserved on-land in ophiolite complexes characteristically exhibits a transition zone over meters to several hundreds of meters from gabbroic rocks crystallized from magmas in the crust, to an underlying section of monotonous depleted peridotites corresponding to the residues of the generation of magmas. The sharp physical contrast in density and seismic velocity between these materials has resulted in this boundary being widely equated with the seismic Moho in the ocean basins. The relatively uniform depth of the Moho, has in turn been used to suggest that crustal thickness, particularly at fast-spreading ridges, is similarly uniform across the ocean basins. This interpretation was supported by the 1971 Penrose Conference ophiolite model which directly equated seismic structure of the ocean crust with an idealized lithologic column constructed from ophiolites. Identification of seismic Moho with the base of the gabbros is the linchpin on which estimates of the volume of past and present basaltic volcanism in the oceans, and therefore the transfer of heat and mass from the interior of the earth to its crust, oceans and atmosphere, is based.

The direct equation of the seismic Moho to the crust mantle boundary, however, has been increasingly questioned. Hess in 1962 believed that the persistent depth to the Moho throughout the major oceanic basins could not everywhere reflect a uniform accumulation of basalts and gabbros. He proposed instead that it represents the transition from serpentinized to fresh peridotites. This interpretation is now supported by evidence from slow spreading ridges, showing common exposure of serpentinized peridotites at the seafloor. It is also supported by recent work on ophiolites showing that the gabbros are variable in thickness. At fast spreading ridges, estimates of the quantity of gabbros needed to account for the extent of fractionation of basalts consistently fall short of the typical thickness of seismic Layer 3 (i.e. the gabbroic layer in the Penrose Conference ophiolite model). This means that the seismic Moho does not always represent the base of the gabbros. The question that Hess raised nearly four decades ago is therefore still with us. We need to drill a full section of ocean crust into the upper mantle in order to resolve this most fundamental of problems in earth sciences. In the course of doing this, we will resolve a host of problems connected with the origin, structure, and history of the ocean crust, and determine what is returned to the mantle at subduction zones.

The past twenty years of ocean crust studies, including drilling, have also revealed important and consistent differences between slow- and fast-spreading ridges. The most important contrast is probably the scale at which axial segmentation influences the general crustal architecture. Fast-spreading ridges such as the East Pacific Rise have far more regular topography and seismic structure, suggesting that their crustal structure is relatively homogeneous in time and space. At slow-spreading ridges such as the Mid-Atlantic Ridge, the thickness of the seismically defined crust varies over scales of 20 to 100 km, from about 6-9 km, to less than 3 km near axial discontinuities. These differences make it clear that we cannot resolve Hess's fundamental question, which he posed for all ocean basins, with a single hole on the flank of a single ridge. Accordingly, an integrated scientific program of ultradeep drilling on both fast and slow-spreading ridges is required.

Questions to be Addressed

- Is the seismic Moho an alteration boundary within the mantle or does it mark the base of the plutonic crust?
- Does seismic crustal thickness provide a reliable estimate of magmatic budget?
- What is the composition and melting history of unaltered mantle peridotite?
- How does melt react with mantle rocks and how do their plastic flow properties compare with seismically measured anisotropy?
- How is melt transported from the mantle to the crust and what is the role of the transition zone?
- Do typical layered gabbros, commonly seen in ophiolites exist in oceanic crust, and if so how do they form?
- How is melt transported and stored in the crust, and what processes (magmatic, tectonic) does it undergo during crust formation?
- How deep does hydrothermal alteration extend, what controls its distribution, and how does it affect the mineralogy, composition, and rheology of the rocks?

- What role do the lower crust and upper mantle play in the origin of marine magnetic anomalies?
- How does the seismic layering of oceanic crust correlate with crustal lithology?
- How does the architecture of crust generated at fast and slow spreading ridges differ, and what are the implications for the processes that form the crust?

Chance of Breakthrough

The successful drilling of a complete oceanic crustal section through the seismic Moho into the upper mantle would address longstanding and fundamental questions in the earth sciences including the origin of seismic Moho and the validity of ophiolitic models for lower oceanic crust and mantle .

(1) If it could shown that the seismic Moho, even at a fast spreading ridge, does not generally coincide with the base of the mafic crust, this would overturn a model for the origin of the oceanic Moho that has been widely accepted for over 40 years. If the Moho is generally associated with a serpentinization boundary within the mantle, as originally proposed by Harry Hess, this would significantly change total magma budget estimates for mid-ocean ridges with major implications for current mantle partial melting models. It would also have fundamental implications for mass and chemical fluxes at subduction zones.

(2) Ophiolites have been used for decades as an analogue for the structure and composition of the oceanic lithosphere, and the processes forming oceanic crust. While this model has been successful in predicting many discoveries at mid-ocean ridges, a direct comparison of the *in situ* properties of oceanic crust with ophiolites has only been possible for the uppermost crust, especially along fast spreading ridges. We still do not know if ophiolites provide a good model for the composition and formation of the lower crust. For example, it is not known if layered gabbros which are a common feature in ophiolites, exist also in oceanic crust. If it could be shown that ophiolites are good analogues to oceanic spreading centers, then this would allow us to confidently exploit these unique exposures to better understand ocean crustal formation.

Experimental Design

More than 30 years of technical problems in deep crustal drilling using conventional rotary, riserless drilling techniques clearly demonstrate that riser drilling is essential to drill through an entire crustal section.

Objectives

(1)Highest priority
- a single deep hole through an entire crustal section, through Moho, into upper mantle on fast spreading crust.

(2) Lower priorities
- a single deep hole through an entire crustal section, through Moho, into upper mantle near a <u>segment center</u> on a slow spreading ridge;
- a single deep hole through an entire crustal section, through Moho, into upper mantle near a <u>segment end</u> on a slow spreading ridge.

Strategy

Highest priority is obtaining a complete crustal section on crust created at a fast spreading ridge for two reasons: (1) because the crust is expected to be much more homogeneous in time and space, and (2) because we know less about the lower crust and upper mantle compared to slow spreading ridges.

Holes should be drilled off-axis at a site which is 20-30 Ma corresponding to a water depth of about 4000 m and temperature at the Moho of 250°C. Non-riser pilot holes should be drilled to depths of several hundred meters to investigate the characteristics of optimum site for deep drilling.

An intermediate depth hole (~ 3 km bsf) should be drilled e.g. in a Western Pacific back-arc basin on ~10 Ma old crust to test the feasibility of a 2.5 km riser system to drill deeply in oceanic crust and sample upper portions of Layer 3.

Site Criteria

Fast Spreading Crust

Geographic location:	EPR; >15°N or ~15°S; ~30 Ma old crust
Water depth:	4,000 m or greater
Penetration depth range:	7 km below sea floor
Hydrocarbon potential:	none
Contamination:	petrologists and geophysicists will take anything
Lithologies:	thin sediment cover (<100m); igneous rocks; uppermost crust fractured
Industry experience:	none; but some DSDP/ODP experience
Other criteria:	3-D seismics with good Moho reflection; typical oceanic crustal and upper mantle velocity structure; center of magnetic anomaly, regular abyssal hill topography, not near seamounts.

Slow Spreading Crust

Geographic location:	MAR; >15°N; 10-30 Ma crust
Water depth:	4,000 m or greater
Penetration depth range:	4-7 km below sea floor
Hydrocarbon potential:	none
Contamination:	petrologists and geophysicists will take anything
Lithologies:	thin sediment cover (<100m); igneous rocks; uppermost crust fractured
Industry experience:	none; but some DSDP/ODP experience
Other criteria:	3-D seismics with typical oceanic crustal and upper mantle velocity structure; center of magnetic anomaly.

Technological requirements

- Highest possible percentage of core recovery
- High-temperature logging tools (up to 300°C)
- Oriented cores for paleomagnetics and tectonic study
- Directional drilling holes with logging
- Borehole seismic and hydrogeologic experiments
- Legacy hole capability

Infrastructure requirements

- advanced analytical labs (paleomag, phys properties, thin section, petrography, XRF, XRD, ICP etc.)
- on-line drill mud gas analysis

Collaboration

Collaboration with InterRidge and ICDP; extensive pre-drilling site characterization will be necessary (multibeam bathymetry, gravity, magnetics, 2-D and 3-D reflection/refraction seismics, heat flow, rock sampling), as well as ODP Phase III drilling.

Water-Rock Reactions and the Evolution of the Oceanic Crust

Background

The oceanic crust comprises more than 70% of the Earth's surface and represents the product of complex interactions between magmatic, hydrothermal and tectonic processes. Post-emplacement water-rock reactions during both hydrothermal alteration and low temperature weathering result in the transfer of mass and energy between the lithosphere and hydrosphere. These reactions play a role in regulating the chemistry of seawater and in the formation of massive sulfide deposits on the seafloor. In addition, these reactions influence the chemical composition of the oceanic crust which is recycled at subduction zones. However, the impact of the water-rock reactions on global geochemical mass balances has been the subject of considerable debate and needs to be quantified.

There are currently two models for the mechanism of heat transfer between the heat source and the circulating fluid. The first may be typical of fast-spreading ridges and involves conductive transfer of heat across a thin brittle/ductile interface immediately above a magma chamber. The second may be operative at some intermediate and slow spreading ridges and predicts convective transfer of heat through cracks into and beneath a frozen magma chamber. In order to address questions related to the elemental exchange during hydrothermal reactions and the heat transfer mechanisms, it is necessary to drill into an active hydrothermal system and through the "reaction zone"--the region where the reactions are believed to be the most extreme-- into the underlying boundary layer where heat is being transferred from the source to the hydrothermal fluid. Previous attempts to drill in these types of environments have met with only partial success due to the technological limitations of the drilling capabilities of the *JOIDES Resolution*. As the crust spreads away from the ridge axis, low temperature weathering reactions continue until the crust becomes sealed at ~ 60Ma. The chemical exchange during some of these water-rock reactions counteract those of the high temperature reactions, and so the chemical composition of older oceanic crust represents the integrated net effect of all the water-rock reactions.

A major recent finding has been the discovery of the existence of microorganisms deep within the oceanic crust. The nature and extent of this subsurface biosphere remains completely unknown and will be a key component of deep drilling within any crustal holes. However, the hydrothermal vents are a particularly exciting target. Hyperthermophilic archaea which grow under conditions of high temperature and pressure have been isolated from hydrothermal fluids.

However, it appears that, in many cases, their optimal pressure for growth is greater than the environmental pressure, suggesting they may have originated from deeper depths. These hyperthermophiles are at the root of the phylogenetic tree, and so studies of these archea will provide very important clues to the identity of the common ancestor and the origin of life. An additional important property of the common ancestor must be barophily, since hyperthermophiles are also adapted to a high pressure environment.

Questions to be Addressed

- What is the depth and nature of hydrothermal interactions in the crust?
- What is the chemical and physical nature of the hydrothermal reaction zone?
- What is the lateral heterogeneity of the hydrothermal reaction zone?
- How do fluid compositions change in the upflow zone between the reaction zone and the seafloor?
- What is the flux of magmatic volatiles at the base of the hydrothermal reaction zone?
- What are the mechanisms for the growth and evolution of seafloor mineral deposits?
- What is the nature, diversity and extent of the subsurface biosphere?
- What is the nature of the boundary layer between the heat source and the circulating fluid, and what are the differences in heat transfer mechanisms between fast and slow spreading ridges?
- How is the crust chemically and physically modified as it is transported away from the ridge crest?
- What are the magnitudes and directions of elemental exchanges, and what is their role in geochemical mass balances that affect the compositions of seawater, sediments, and oceanic crust?

Chance of Breakthrough

1) Current models of hydrothermal circulation and the formation of sulfide mineral deposits are based on ophiolite analogies, laboratory experiments, and studies of seafloor hydrothermal fluids. Recovery of core and sampling a vertical section of an active hydrothermal system will be the first test of these models.
2) Drilling into the boundary layer between the heat source and circulating fluid at appropriate targets on slow and fast spreading centers will test the current models of heat transfer mechanisms. Any observations of the nature of this layer will represent a significant breakthrough in our understanding of the mechanisms of heat transfer in hydrothermal systems.
3) Confirming the presence of a substantial subsurface biosphere will have enormous scientific and societal impact. This heretofore unquantified subsurface biosphere has the potential to revolutionize our understanding of life on Earth. Recent studies suggest that microorganisms may play a significant role in the alteration of the oceanic crust, and that hyperthermophilic microorganisms have already had a major impact on biotechnological applications. Further discoveries of fauna living in a variety of subsurface environments may give rise to further important industrial applications.
4) The chemical composition of off-axis oceanic crust represents the integrated effects of all types of alteration processes. Determination of the mineralogical and geochemical composition of this altered crust will provide the first realistic estimate of the nature of the oceanic crust being subducted.

Experimental Design

1) Reaction zone drilling

One vertical hole to depths ranging from 2 to 4 km should be drilled as close as possible to an active hydrothermal upflow zone, and should penetrate through the reaction zone of a hydrothermal system. Azimuthal directional drilling within the hydrothermal reaction zone will investigate lateral heterogeneities. To address the heat transfer objectives, single holes should be targeted in a hydrothermal system along both slow and fast spreading ridges, as well as in a back-arc environment. A complete logging program of physical and chemical properties measurements should also be conducted.

These studies should be combined with fluid flow and monitoring experiments (see Working Group 5 report). Drilling-related experiments will primarily be focused on two aspects: 1) defining the sub-surface physico-chemical permeability and chemical evolution of hydrothermal fluids which pass through it, and 2) monitoring the physical and chemical properties of these fluids over time scales of several years. Specifically, drilling and borehole instrumentation can be used to assess the 3-D pattern of: lithostratigraphy and alteration assemblages, porosity and permeability structure, and their relationship to fracturing, T-P conditions, pore fluid composition and flow direction (both chemical and biological components).

2) Crustal Aging

This objective requires that two holes are drilled along a flow line. The first would be drilled in ~5 Ma crust beyond axial high temperature hydrothermal circulation, and the second hole drilled in 30 Ma-old crust or older would give the integrated results of alteration processes. The latter hole could be coincident with that proposed to penetrate through the Moho. In order to maximize the scientific results, this drilling should be performed in areas where considerable geophysical and geochemical data are already available (e.g. 17.5°S on East Pacific Rise) An extensive logging program including measurements of physical and chemical properties should be implemented in order to assess crustal sealing processes, the effects of alteration on the seismic properties of the crust and upper mantle, and the nature of crustal and mantle reflectivity and anisotropy.

3) Biology Studies

Principal biological experiments include extraction and sequencing of DNA from molecular diversity studies (e.g. PCR amplification, cloning, phylogenetic analysis, etc.) and attempts to culture microorganisms at ambient temperatures and pressures. The success of these studies require samples as uncontaminated with drilling mud as possible. In addition, background studies of the drilling mud will also be carried out.

Technological Requirements

Drilling a hydrothermal system in a slow-spreading ridge environment as well as drilling a transect for crustal aging objectives will require the capability of riser drilling in >2,500 m water depth. However, it is possible that sites at water depths of <2,500 m could be found on fast-spreading ridges and in back-arc or fore-arc environment. High core recovery will be critical to determining lateral heterogeneity within the hydrothermal reaction zone.

High temperature (> 400°C) and bare rock drilling capabilities will be necessary, as well as directional drilling. It is critical that fluid sampling techniques will be developed to minimize contamination from drilling mud. The design and development of high temperature logging tools will be necessary in order to reach this goal due to the expected range of temperatures likely to be encountered (200-400°C). On-line mud gas analysis will be used to monitor mud gas composition, as was done at the KTB site, to determine the critical depth for downhole fluid and gas sampling, and to provide a more quantitative estimate of the volatile magmatic input.

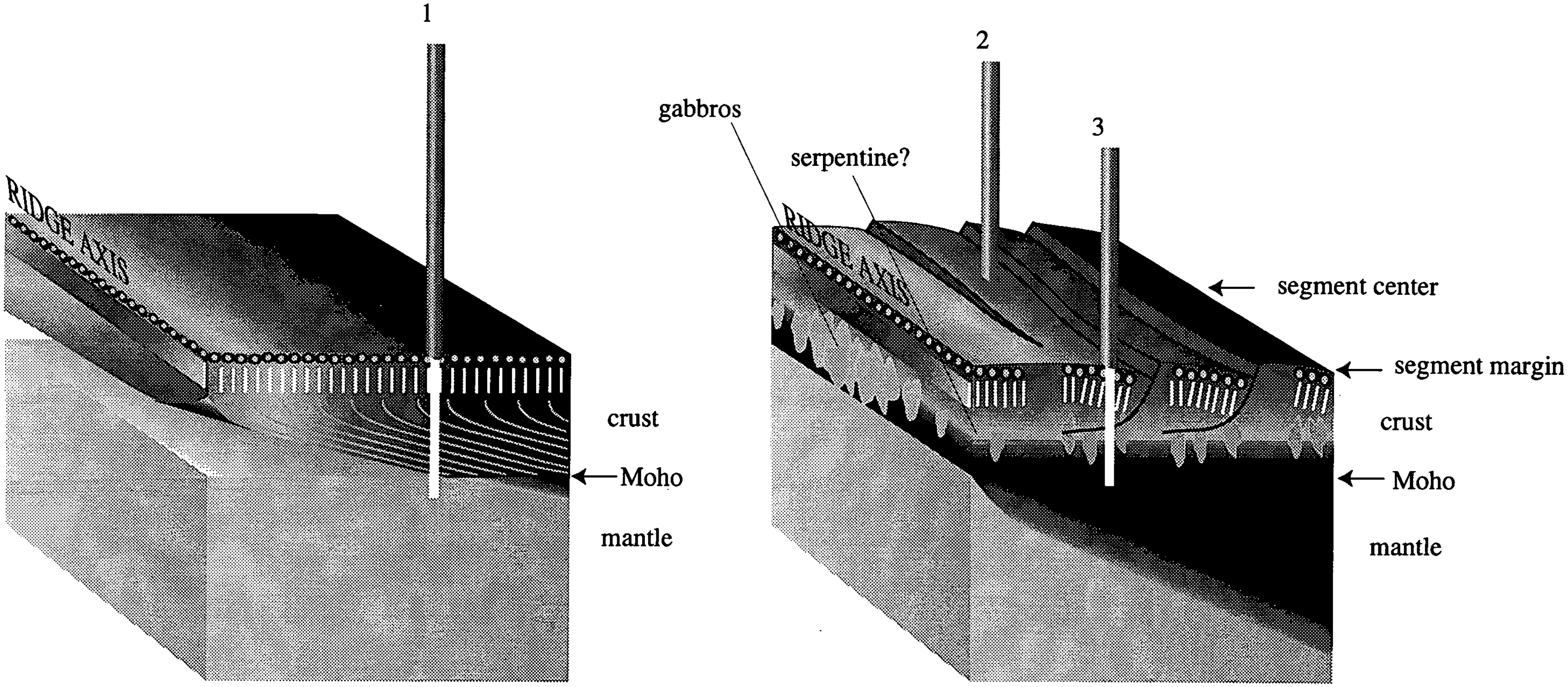
To grow the microorganisms under high pressure and high temperature conditions, we need to use the "DEEPBATH" system developed by the DEEPSTAR project, JAMSTEC.

Infrastructure Requirements

- Capability of riser drilling in >2,500 m water depth
- High temperature logging tools
- On-line mud gas analysis
- Sampling of minimally contaminated fluid samples.

Collaboration Requirements

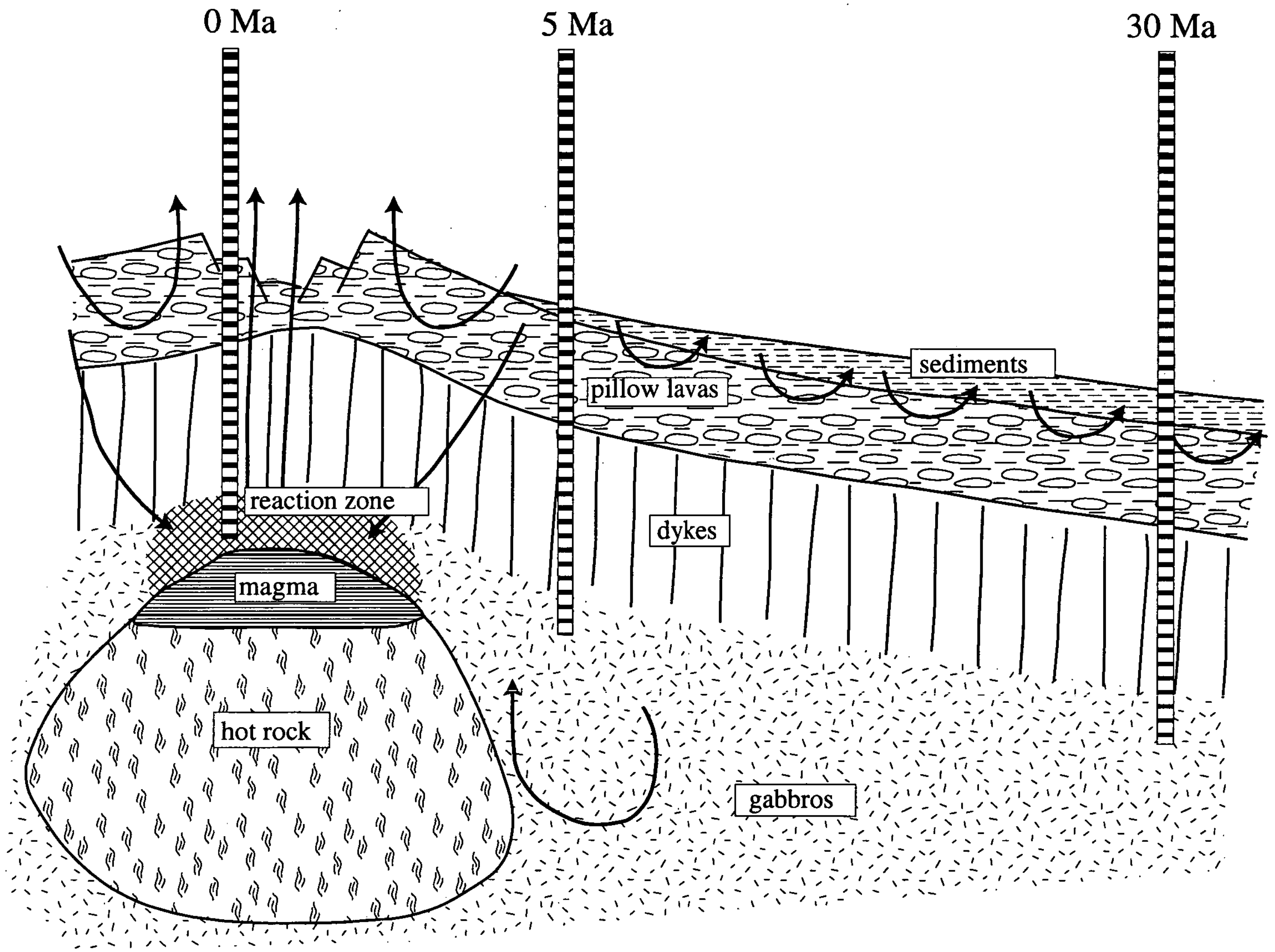
- Collaboration with InterRidge, ICDP, and mining industry.
- Extensive pre-drilling site characterization will be necessary, including multibeam bathymetry, magnetics, seismics, heat flow studies, detailed submersible studies, and sampling of fluids and substrates.



Fast spreading system

Slow spreading system

Fig. 1: Ultra deep drilling of the lower oceanic crust and Moho. (Modified from A. Nicolas's original drawing.)



Fg. 2: Drilling for the study of water-rock reactions and the evolution of the oceanic crust.

Working Group 3 Report
Continental Rifting and Large Igneous Provinces

Executive Summary

Understanding dynamic processes in the mantle and the links among mantle dynamics, plate tectonics (including plate-motion changes and continental breakup), and global change promises to be one of the most exciting frontiers in earth sciences well into the 21st century. Oceans are created by **the breakup of continents**, and the continental margins formed in the process include a spectrum of types, from nearly amagmatic margins to ones with massive accumulations of igneous rock. Even more volumerous mafic edifices, **the Cretaceous oceanic plateaus**, are present in the ocean basins. Although continental rifting is a cornerstone of plate tectonics, many key aspects of rifting, including the principal cause of rifting, are not understood. In contrast, oceanic plateaus and large continental margin volcanic provinces are not obviously explained by plate tectonics and questions about their nature, origins, and global effects are presently at a much more basic level. The chief impediment to progress in each case is a lack of sampling. Deep riser-type drilling is necessary for such sampling.

The highest priority for riser-type drilling on oceanic plateaus is **deep drilling (6 km or more) into giant oceanic plateaus**. This experiment is designed to drill a deep hole through a significant portion of a giant oceanic plateau's volcanic crust. The questions to be addressed by this experiment are 1) where in the mantle do plateau magma sources originate and how do they evolve through time; 2) how are individual plateaus emplaced; what are the magma and volatile fluxes involved; and what is the syn- and post-emplacement uplift and subsidence history; and 3) how is oceanic plateau production related to major changes in the global earth system, including the hydrosphere, atmosphere, biosphere, and geomagnetic field?

Of several recommended rifted margin projects, a high-priority -- but challenging -- experiment is **deep drilling into the continental lower crust and continental Moho**. Very thin (<10km) continental crust just landward of the continent-ocean transition offers the unique possibility of using riser drilling to penetrate the entire crustal thickness, from upper crustal blocks, through attenuated lower continental crust, to the subcontinental Moho. Data obtained by this experiment will provide key insights into understanding of origin and evolution of the continetal crust and upper mantle, as well as the origins of fold-belts.

Introduction

Oceans are created by the breakup of continents, and the continental margins formed in the process include a spectrum of types, from heavily sedimented to sediment-starved, and from nearly amagmatic margins to ones with massive accumulations of igneous rock tens of kilometers thick. Even more enormous mafic edifices, the large oceanic plateaus, are present in the ocean basins; together with continental volcanic margin provinces and continental flood basalts, they are termed large igneous provinces or LIPs (Fig. 1). Although continental rifting is a cornerstone of plate tectonics, many key aspects of rifting are not understood; to a very large extent this is because of a lack of sampling. In contrast, oceanic plateaus and large continental margin volcanic provinces are not obviously explained by plate tectonics and the questions about their nature, origins, and global effects are presently at a much more basic level. Again, however, the chief impediment to progress is a lack of sampling. Quite simply, deep riser-type drilling is necessary for such sampling.

Oceanic Plateaus

Background

Convective motion in the solid earth directs the exchange of mass and energy between the planet's interior and exterior. However, the current dynamic state, as manifested by the dominance of plate tectonics, may be quite different from conditions at times in even the fairly recent geological past. Understanding whole-earth-scale geodynamic and geochemical changes through time with the aim of predicting future global changes is one of the exciting frontiers in earth sciences. Of particular interest, the timing of major convective pulses within the mantle may have coincided with major changes in climate, mass biological extinctions, changes in geomagnetic field reversal frequency (onset of superchrons), and important episodes of continental drift. The pulsation of the mantle has been recorded in massive igneous activity, the most dramatic products of which are LIPs. The largest LIPs are several Cretaceous intraoceanic plateaus, which are theorized to reflect large-scale mantle upwelling quite different from that associated with normal hotspots and plate tectonics. Figure 2 summarizes the apparent temporal relations between LIP activity and other first-order global changes; unfortunately, because sampling, and thus the geochronological and geochemical data base for plateaus, is minuscule, possible genetic links of plateau emplacement to other major events need badly to be clarified and quantified. Similarly, both plateaus and continental margin LIPs are increasingly recognized as important components in the growth of continental crust, but their bulk compositions are very poorly known. The only way to systematically sample plateau crust is by drilling, and only riser-type drilling can provide sampling of deep stratigraphic basement sections.

Key Questions

General

- Where in the mantle do plateau magma sources originate and how do they evolve through time?
- How are individual plateaus emplaced (cataclysmically in geologically very brief outpourings, in two or more separate pulses, or semi-continuously over periods of 10-40 Myr);

what are the magma and volatile fluxes involved; and what is the syn- and post-emplacement uplift and subsidence history?
- How is oceanic plateau (and other large LIP) production related to major changes in the global earth system, including the hydrosphere, atmosphere, biosphere, and geomagnetic field?

Specific

Four first-order problems in the characterization and quantification of plateau production and its effects during Cretaceous time can be addressed directly by deep ocean drilling.

1. Source composition and location, melting conditions, melt migration and emplacement

Massive decompressional melting of mantle is required to make oceanic plateaus and continental margin LIPs. Fundamental, but very poorly known, aspects of plateau formation include the original location of the principal source (base of the upper or lower mantle?), thermal conditions, history of melt production and migration, relative contributions of other mantle source reservoirs (e.g., MORB-source mantle), and related hydrothermal metamorphism and fluid fluxes. Horizontal and vertical sampling of oceanic plateau crustal stratigraphy will provide requisite compositional data to

(a) Determine compositional and petrological range. This information is essential to estimate location, composition, and extent of partial melting of the magma source, estimate bulk crustal composition and density, and define magma migration mechanisms and plumbing systems. Because parental basalt magmas originate at different mantle depths and follow different time-temperature paths, petrological and geochemical studies of basaltic rocks, combined with estimates of magma production rates, will provide insight into the causes of anomalous melting.

(b) Determine spatial distributions of compositions and compositional gradients. Such systematics may reflect the size of the melting region, source mixing processes, and temporal variability of melts.

2. Chronology of oceanic plateau magmatism

A fundamental distinction between Cretaceous oceanic plateaus and modern hotspot volcanism is the rate of melt production. The few available plateau basement samples yield narrow age ranges for individual plateaus and some strongly bimodal age distributions, suggesting cataclysmic or episodic volcanic events with magma fluxes significantly greater than those at modern hotspots. In addition, the sparse existing age data suggest that constructional episodes of different oceanic plateaus occurred contemporaneously, in turn suggesting an episodicity of the global magmatic flux in Cretaceous time. The primary objectives:

(a) Quantify the times and duration of individual magmatic events and estimate time-averaged magmatic fluxes over the entire period of formation. Estimates of magma volumes from combined age and geophysical data (seismic reflection and refraction, gravity, perhaps magnetic data) will provide critical information on the mechanism(s) of plateau formation.

(b) Establish temporal relationships among different Cretaceous plateaus. Are there simultaneities in emplacement times of oceanic plateaus, or episodicities?

(c) Quantify the contributions of plateau magmatism to the global magmatic flux throughout the Cretaceous period in order to understand relationships between plateau emplacement and other global processes such as changes in patterns of plate subduction and spreading, plate velocities, true polar wander, motion between Atlantic and Pacific hotspot groups, and magnetic field reversal frequency. Also, in combination with geochronological data, high-resolution paleomagnetic records will help elucidate possible relationships between the Cretaceous Normal magnetic superchron and mantle upwelling patterns.

3. *Relationships between plateau and ridge magmatism*

Oceanic plateaus are emplaced in tectonic environments ranging from purely extensional to intraplate. Controversy exists as to whether changes in plate motion, especially continental breakup, can initiate plateau formation or whether plateau magmatism instead has a major influence on plate motion changes. Knowledge of the precise temporal relationship between plateau emplacement and changes in plate motion is critical, because Cretaceous oceanic plateaus are close in age to adjacent oceanic crust, implying that plateau formation and seafloor spreading patterns may be related. To determine the original tectonic setting of plateaus and whether they preceded or closely followed changes in spreading geometry, the age and geochemical relationships between plateau and nearby ridge magmatism must be elucidated with high-quality geochemical data and high-resolution age data. Structural and stratigraphic relationships between plateau and adjacent ocean crust also must be determined through detailed lithostratigraphy combined with seismic stratigraphy.

4. *Environmental impact: large mantle upwellings as an instigators of global change?*

Voluminous pulses of igneous activity affect the physical and chemical character of the mantle, oceans, atmosphere, and biosphere to a largely undetermined extent. Much of the progress in assessing these effects will come from improved knowledge of plateau ages and magmatic fluxes, as noted above. In addition, submarine and subaerial volcanism have substantially different effects on the earth's surface environment. Studies of drill core samples, combined with geophysical information, will permit estimates of the proportion of submarine to subaerial volcanism, of the depth ranges at which submarine lavas were emplaced, and of the amount of degassing of volatiles. Likewise, the role of hydrothermal and metamorphic processes in plateaus and their possible effects on the surrounding ocean are virtually unknown, although it is clear that the thermal and permeability structure of pre-existing oceanic and transitional crust invaded by oceanic plateau magmas differs from that at mid-ocean ridges. Indeed, gradients in trace metals resulting from hydrothermal activity may "fingerprint" each oceanic plateau and enable precise correlation of its formation with global oceanic anoxic events.

Chances of Breakthrough

Carefully selected deep-drilling sites on oceanic plateaus offer high possibilities for major scientific breakthroughs. If the temporal and compositional development of a giant oceanic plateau can be documented, related to a mode of mantle circulation fundamentally different from that of the Cenozoic, and a causal relationship to one or more types of global environmental change established, there is no doubt that the impact on the geosciences will be of lasting significance.

The Experiments

We have devised two experiments (see Fig. 3) which address, in particular, the outstanding objectives of elucidating Cretaceous mantle dynamics and the relationship between oceanic plateau magmatism and global change. The first experiment is a higher priority for riser drilling.

Working Group 3 Report

1. Deep hole in a giant oceanic plateauThis experiment is designed to drill a deep hole through a significant portion of a giant oceanic plateau's crust (i.e., one with a crustal volume in the 20-60 million cubic kilometer range). Deep drilling is required for thorough study of Cretaceous oceanic plateaus because exploratory drilling of 150-300 m basement holes, as planned in the second and third phases of ODP, will provide sampling in any given area corresponding to only about 1% of the thickness of the giant plateau (total thickness 20 to 40 km). The scientific rationale for this experiment is to

(a) quantify the time interval for formation of the giant plateau and the volume of magmatic products as a function of time.

(b) understand the role of mantle plumes in forming the plateau by determining the relative roles of plume, asthenosphere and lithosphere as sources of volcanism. Evaluation of the plume contribution is vital to deciphering source origin and location.

(c) examine any possible link between mantle and core processes, through high resolution paleomagnetic data.

(d) obtain good recovery of sedimentary layers within the volcanic stratigraphy and above it to document syn- and post-emplacement environmental changes and information on paleodepth and uplift/subsidence history.

Technological requirements are as follows.

- Water depth: 2,000-4,000 m (many good sites <3,000 m exist)
- Sediment thickness: ≤2,500 m, mostly 500-1,000 m
- Time constraints: approximately 300 m drilled over 10 days, i.e. about 200 days of drilling minimum (i.e., at least 6 km of basement penetration)
- Need coring with high recovery
- Need full suite of well logs
- Need orientated cores and amagnetic drilling

2. A Deep Hole in the Volcaniclastic Apron of a Giant Oceanic Plateau

Determining realistic volume flux histories of individual oceanic plateaus is critical in differentiating various models of the origin and emplacement of oceanic plateaus -- but such information is lacking. Aprons of volcaniclastic sediments shed from a plateau edifice may offer a valuable record, complementary to that in the lava stratigraphy on the plateau itself, for determining volcanic history (especially information on earlier stages of volcanism beyond the reach of even OD21 drilling). Such aprons may also provide important information on paleodepth history, particularly adjacent to the plateau. We propose to drill a "reference hole" near the margins of a giant oceanic plateau to recover a more complete volcanic history than drilling on the plateau alone would provide.

Technological requirements are as follows.

- Water depth: 4,000 m
- Sediment thickness: ?
- Time constraints: ?
- Need coring with high recovery rates (>60%)
- Need full suite of well logs

Why riser drilling?

To carry out the experiments listed above, riser drilling is needed for achieving

- higher recovery in both proposed holes, and
- deeper penetration (>6,000 m) for a thick, and ideally a complete, section through the volcanic sequence in the deep hole.

Related Requirements

Multichannel seismic profiling in a grid sufficient to identify the internal structure of the volcanic sequence. Detailed gravity data (the denser the coverage the better; i.e., not only satellite-derived data) would be useful, as well as magnetics and bathymetric coverage.

The hole position must be in a section where structural disturbance is limited; in terms of survey logistics, the site can be assessed in a step-by-step manner beginning with reconnaissance profiles, then long lines, then increasingly detailed coverage as required.

Collaboration

International collaboration is required to obtain integrated and complete knowledge of the long cores. Diverse expertise, from sedimentology, geochemistry, paleomagnetism, geochronology, and geophysics, will be necessary for the success of this project. Links between mantle tomographic studies are envisaged, and possibly with workers studying the growth and nature of continental crust. Interaction with the IAVCEI Commission on Large-Volume Basaltic Provinces is highly advisable.

Mantle Dynamics and Lithospheric Deformation in Continental Breakup

Background

The formation of rifted margins results in the formation of most of the world's hydrocarbon resources, and the continued search for new resources in deeper water has driven the development of commercial deep-riser systems. Moreover, most of the world's population resides on ocean margins and within the zone affected by both sea-level variations and margin instability. In the intensifying search for energy resources, it is imperative to understand the formation, development, and stability of rifted margin systems. Despite their societal and economic importance, many of the processes that shape these margins are poorly understood. The OD 21 program is uniquely poised to answer one of the most fundamental remaining questions in plate tectonics: to define and quantify the processes that create the forces that rip apart continental lithosphere during the birth of an ocean.

Research over the last few decades has revealed that extensional continental margins have a great variety of structural, magmatic, and stratigraphic styles. Various international thematic workshops in recent years have identified a number of first-order problems associated with the formation and evolution of margin systems; these meetings also have spawned research initiatives aimed at understanding the fundamental processes involved via multidisciplinary programs integrating field experiments, numerical simulations, and laboratory studies. Several of these initiatives specifically emphasize the importance of riser drilling for the requisite deep penetration and for blowout prevention in these frequently hydrocarbon-prone settings.

From previous thematic workshops and the discussions held at CONCORD, the fundamental processes that must be addressed include (1) *lithospheric deformation:* the mechanisms determining the amplitude and spatial partitioning of strain within the deforming lithosphere; (2) *mantle dynamics and magmatism:* conditions in the underlying convecting mantle and their evolution, magma sources, and the processes associated with magma emplacement; (3) *basin-forming systems and stratigraphic implications:* the timing and spatial distribution of discontinuities within the stratigraphic record and what they mean in terms of lithosphere deformation, sediment transport, and depositional and erosional processes. A good understanding of the stratigraphic record is critical because the sediments are the "tape-recorder" of vertical lithospheric motions (i.e., deformation). (4) A fourth topic of considerable interest is the *nature of lower continental crust and the continental Moho.*

Key Questions

1. What controls the 4-D distribution of extension and strain in the lithosphere and how is it balanced (a) vertically, (b) along a margin (i.e., segmentation), and (c) across a margin. How does strain evolve through time?

2. What are the thermal, rheological, and mechanical implications of this strain balancing? What are the nature and role of crustal detachments in active and mature rift systems? How does the lower continental crust thin and how strong is thinned continental lithosphere?

3. What is the mineralogical and chemical composition of the thinned continental crust beneath rifted margins? What is the nature of the continental Moho and can its age be determined? What does such information imply about the bulk composition of the lower continental crust?

4. What is the nature of rift-margin magmas and their sources (roles of plume vs. non-plume, MORB mantle, and continental lithospheric mantle), how do the magmas migrate toward the surface, and what are the emplacement mechanisms?

5. What is the physical and chemical significance of the ocean-continent transition: is it a region of strain-balancing between the crust and the lithospheric mantle and/or the focus of magma flow during extension, leading to the emplacement of seaward dipping reflectors?

Potential Scientific Breakthroughs

One of the most fundamental problems left unsolved by plate tectonics is the cause of continental rifting and breakup. Understanding dynamic processes occurring within the mantle (including the role of plumes) and crust at pre-, syn-, and post-rifting stages is clearly the key objective. Recognizing the diversity of passive margin structural styles produced during continental rifting and the likelihood that a continuum exists between magmatic and amagmatic end-member types, we have identified five generic riser-drilling experiments: rifted margin sedimentary strata, magmatic accumulations along margins, detachment surfaces, continental lower crust and Moho, and embryonic rifting. Although we have not formally prioritized these proposed projects, drilling into the lower crust and Moho, albeit very challenging, would be of great interest to a wide variety of geoscientists.

Why riser drilling?

The immense contribution of OD-21 is the promise of substantial increases in the ability to drill high-quality holes in challenging geologic environments. For the margin experiments outlined below, riser-type capability is imperative for

(1) increased hole stability and greater recovery of sediments and basement rocks
(2) increased penetration
(3) blowout prevention in potentially overpressured areas (e.g., those with likely hydrocarbons).

The initial window of operation for OD-21 riser drilling (500-2,500 m water depths) allows many important margin targets to be attacked, although ultimately it will be necessary to achieve the capability to work in water 4-5 km deep, particularly to study highly thinned and deeply subsided crust.

The Experiments

1) Continental Moho and Lower Crust

During rifting, continental crust that is typically 35-40 km thick is strongly attenuated prior to accretion of steady-state oceanic crust. Although the architecture of the resulting conjugate rifted margins can vary substantially, several margins, typically amagmatic, show continental crust thinned from 15-0 km extending over horizontal distances of 100-200 km (Fig. 4). The thinned continental crust consists of rotated upper crustal blocks and progressively attenuated lower crust approaching the continent-ocean transition. Very thin (<10 km) continental crust just landward of the continent-ocean transition offers the unique possibility of using riser drilling to penetrate the entire crustal thickness, from upper crustal blocks, through attenuated lower continental crust, to the continental Moho.

Another important reason to improve our understanding of the physical and compositional properties of attenuated continental crust is that it is precisely such crust that is involved in fold-belt generation during arc-continent collisions, perhaps best exemplified by New Guinea in the vicinity of the Woodlark Basin. Structural and lithological heterogeneities and discontinuities inherited from the continental rifting stage will exert a strong control on the crustal architecture of any fold-belt created by collision of a thinned margin with an island arc. In particular, margin-parallel ridges of highly extended lower crust on some amagmatic rifted margins may, subsequent to arc-continent collision, be reactivated and appear as exhumed "pop-up" structures in the new collisional crustal collage, wherein they serve as the sources of siliciclastic molasse-type sediments.

Technological requirements are as follows.

- Riser technology capable of deep penetration (8-10 km) in deep water (4-5 km)

2) Rift margin stratigraphy

To understand the tectonic, sedimentation, and fluid history, as well as the hydrocarbon potential of rifted margins, a thick and complete section should be drilled through selected depocenters of the basins that form along such margins (e.g., see Fig. 5). These basins record the relative importance through time of tectonic subsidence and uplift, sediment supply, compaction, alteration, and diagenetic processes in margin evolution. With a complete sedimentary record, the timing and magnitude of upper crustal strain can be estimated and the margin's thermal evolution can be deciphered. Furthermore, the flux of fluids through the system can be investigated; such knowledge is essential in order to understand how fluids act as the primary coupling agent of the physical and chemical processes controlling sediment transport, deposition, burial, and diagenesis. Reconstruction of the pre-rift sequences in deep petroleum-prone basins is also a high priority in this experiment.

Technological requirements are as follows.

- Water depth -- as shallow as possible (presumably 500 m)
- Penetration depths, a minimum of 8 km to recover a complete stratigraphic record
- Riser *required* for blowout prevention -- needed to drill through overpressurized horizons and hydrocarbon traps -- and enhanced core recovery in unstable and poorly consolidated sections

3) Magmatic margins

Volcanic rifted margins are one class of large igneous provinces, and are characterized by thick lava sequences (>5 km) and the formation of massive amounts of new igneous crust (>20 km). Key questions that riser drilling can help to answer are as follows. (1) What are the sources of magma (lower mantle, upper mantle, lithospheric mantle) and what are their relative proportions? Answering this question will help to quantify the mass fluxes between different mantle reservoirs and is fundamental for understanding mantle convection and its role in continental breakup. (2) What is the nature of the continent-ocean transition on volcanic passive margins? (3) What proportion of extension is accommodated by stretching and tectonism of the continental lithosphere and what amount by the addition of new igneous material? (4) What is the geochemical nature of the earliest oceanic basalts accreted to volcanic margins at the beginning of seafloor spreading, what are the temperatures and depths of melting and how do they vary in space and time? (5) Can volcanic margins form in the absence of a mantle plume source?

A generic volcanic margin drilling transect would include the following targets (see Fig. 6). (1) Drilling on the shelf in the continental rift basins would permit determination of the duration of rifting and the nature of strain accumulation in the crust. (2) Drilling deeply into the main seaward-dipping reflector sequence would provide a vastly greater record of lava chronology and geochemical stratigraphic variation than is presently available anywhere. (3) A "control" well in the adjacent oceanic crust could establish the geochemical evolution of magmatism at the earliest stages of normal seafloor spreading and provide control on subsidence of the spreading center from shallow to normal ocean-ridge depths.

In addition to transects that sample from continent to ocean, along-strike drilling transects are needed to quantify the spatial and temporal evolution of volcanic passive margins. Areas ideal for this purpose would be regions where volcanic and non-volcanic margins are present in close spatial and temporal proximity. Finally, in plume-affected areas, the geochemical and thermal "structure" as a function of distance away from the plume stem needs to be defined.

Technological requirements are as follows.

- Multiple casing strings set above the riser
- Multiple logging suites
- Packers to recover fluids if present
- Directional drilling not required but could be useful

4) Detachment Surfaces

Along some margins, sediment flux from the continent has been sufficiently small that the "syn-rift" section and reflection style of the underlying stretched continental crust can be imaged. Current interpretations suggest that some reflections in these margins are detachment surfaces onto which the normal faults that bound the syn-rift sequence sole (see Fig. 7). Such detachments are widely believed to be the principal means of crustal thinning and thus a critical control in basin formation. In active extensional basins, these detachments are active low-angle faults. In mature basin settings, the origin of these surfaces is unknown but has been suggested to represent either a rheological boundary separating brittle and ductile deformation fields or a compositional boundary separating extended continental crust above from serpentinized peridotite below. Drilling through detachment surfaces, both active and mature, is a major target for which riser drilling with blowout prevention is required.

Technological requirements are as follows.

- Multiple casing strings set above the riser
- Multiple logging suites
- Packers to recover fluids if present
- Directional drilling would be useful

5) *Embryonic rifting*

What are the processes and products accompanying the initial stage of continental rifting? The mechanical and dynamical processes involved in rifting supra-subduction-zone crust may provide useful analogs of rifting in major continental blocks away from subduction zones. Embryonic rifts in areas not affected by plumes are present in several subduction-related settings (e.g., Okinawa Trough, Bransfield Strait, Andaman Sea) and offer the opportunity to characterize, via deep drilling, the structural, magmatic and thermal/subsidence histories of such settings. Information gained via deep riser drilling will enable testing of models for continental extension; for instance, is rifting driven by roll-back or by extension caused by delamination of thickened lithosphere?

Technological requirements are as follows.

- Water depth: 500-4,000 m
- Sediment thickness: 1,000-3,000 m
- Time constraints: approximately 300 m drilled over 10 days, i.e. about 100 days of drilling minimum

COLLABORATION REQUIRED

The objectives outlined above for rift studies are realistic but ambitious. They can be accomplished only through close collaboration with national and international funding agencies, and the oil and gas industry. Indeed, broad support from the entire earth sciences community should be sought. National agencies will be needed to provide all relevant existing geological and geophysical information. Equally important will be to maintain an exchange of information between programs such as the U.S. Margins Initiative at the national level and OD21. International earth-science initiatives (e.g., InterRidge program) will also be needed in the dissemination of information before and during the OD21 program. In the international arena, the International Lithosphere Program (ILP), a joint venture of the IUGG and the IUGS, can play a particularly important role in communicating with the broader earth sciences world through publicizing and explaining the goals of OD21. The International Continental Drilling Program (ICDP) can be considered a sister initiative to ocean drilling.

Oil- and gas-related industry should be an integral part of the program. Partnerships of various sorts with industry are a must for OD21, as exemplified by recent close collaboration of academic and industry groups in attaining major deep-drilling objectives. The latter example, together with the demonstrated willingness of industry to understand the basics of basin architecture, are only two illustrations of the convergence that is already taking place between academic and industry science.

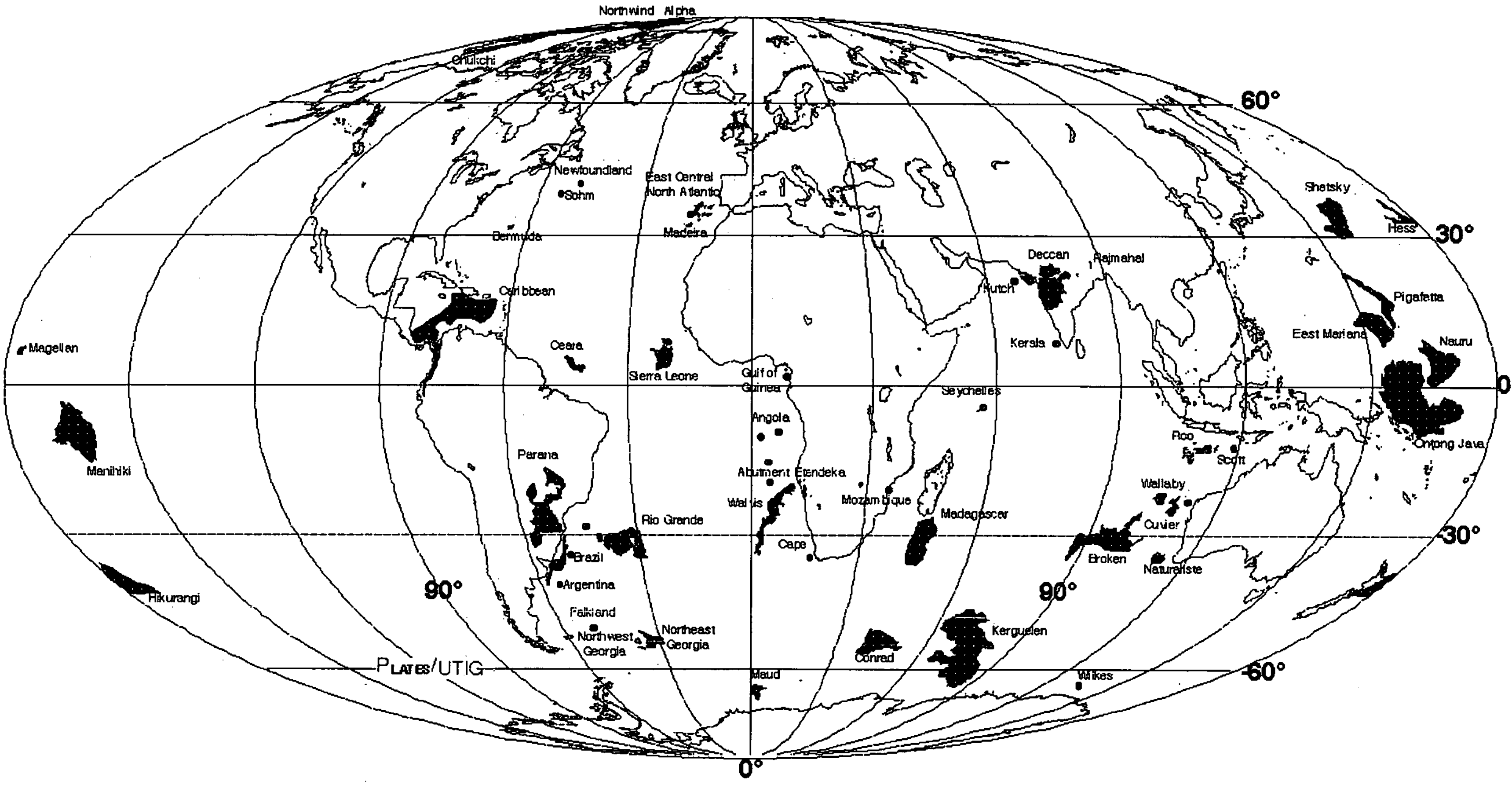


Figure 1. Distribution of Cretaceus LIPs. There are over 20 large oceanic plateaus. (Note that hotspot-type seamount chains included in the figure are sometimes classified as LIPs.) Modified from Coffin & Eldholm (1994).

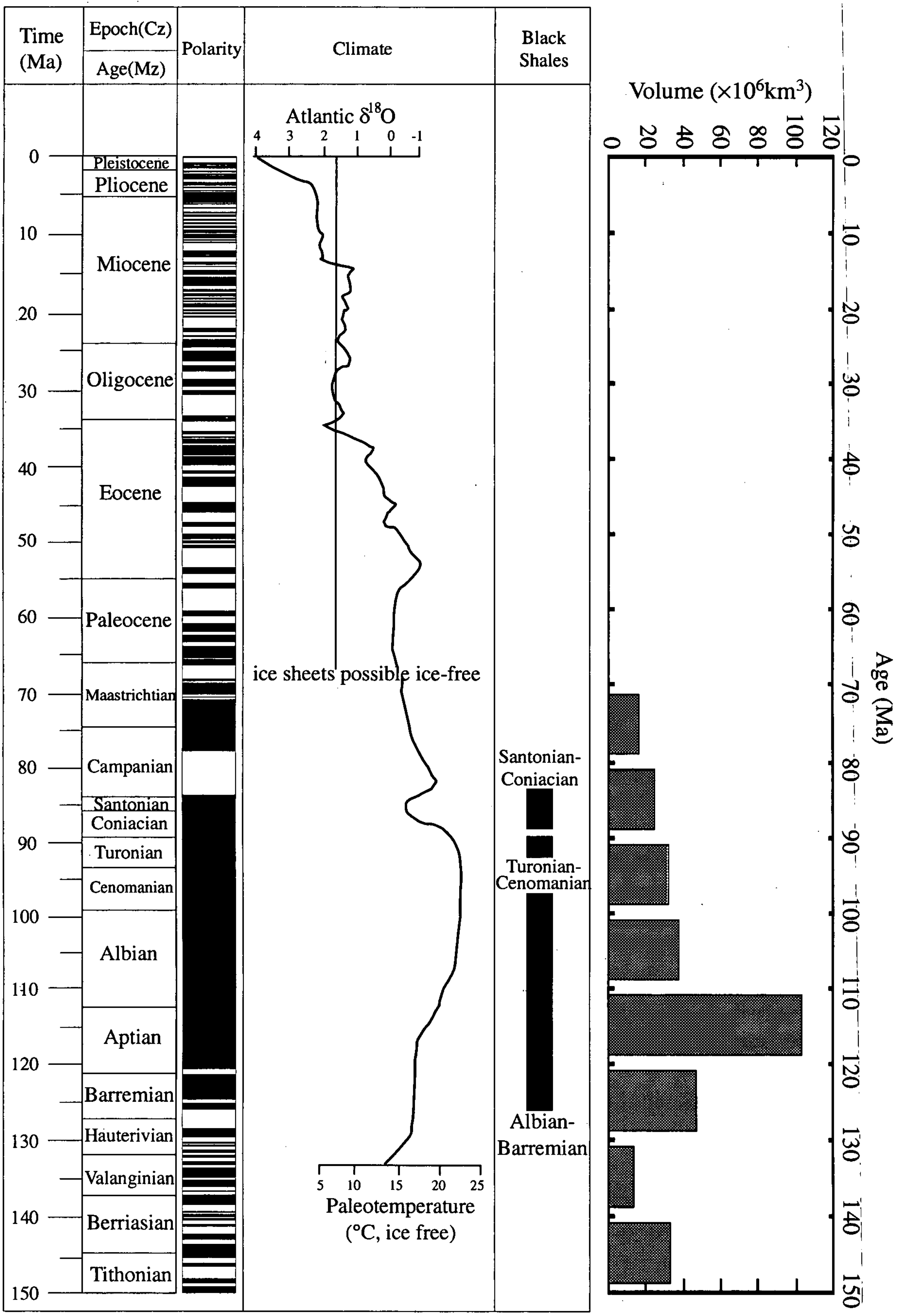


Figure 2. Temporal correlations among oceanic plateau magmatism, geomagnetic polarity, estimated global mean temperature, and black shales. Modified from Coffin & Eldholm (1994).

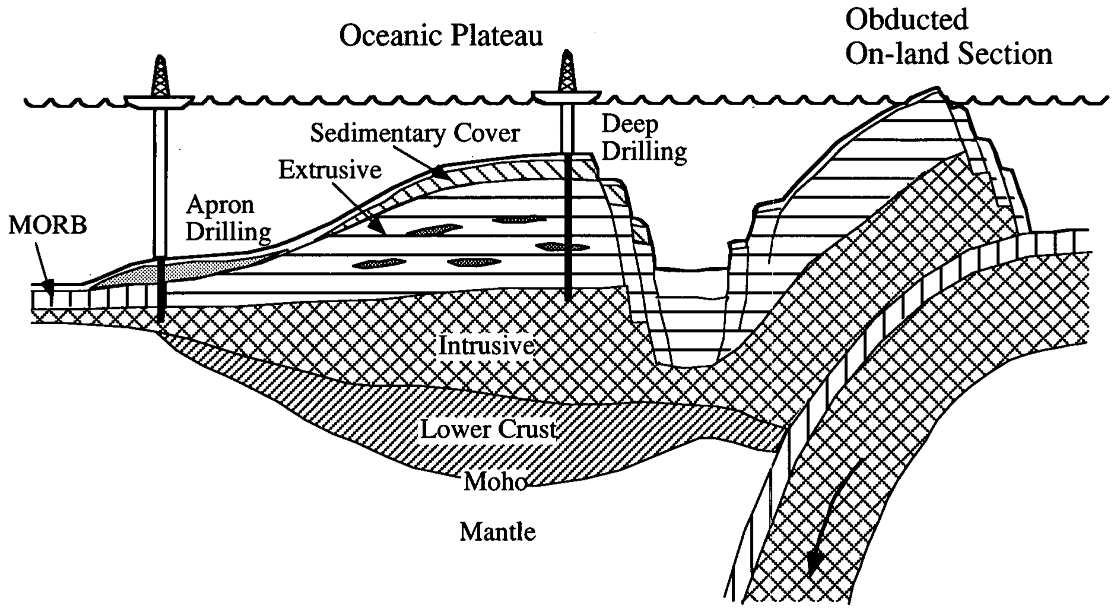


Figure 3. Proposed OD21 plateau drilling strategy. A >6 km-deep hole atop the plateau and a much shallower hole into the volcaniclastic apron will be drilled following suitably detailed surveys and exploratory drilling of 150-300 m-deep holes.

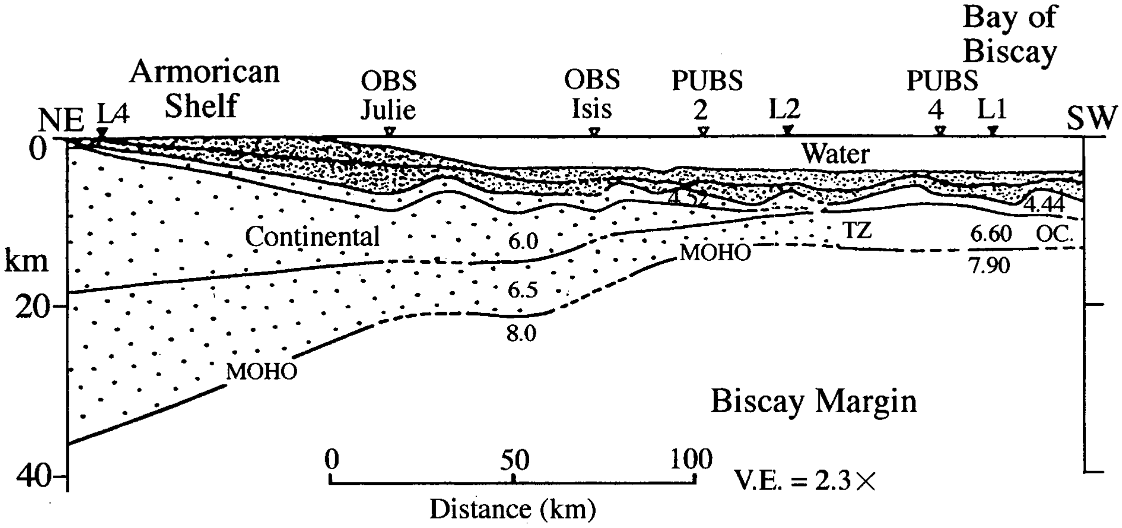


Fig. 4 Velocity structure across a non-volcanic margins.
From Morgan et al., 1989 (NARD-DPG Report)

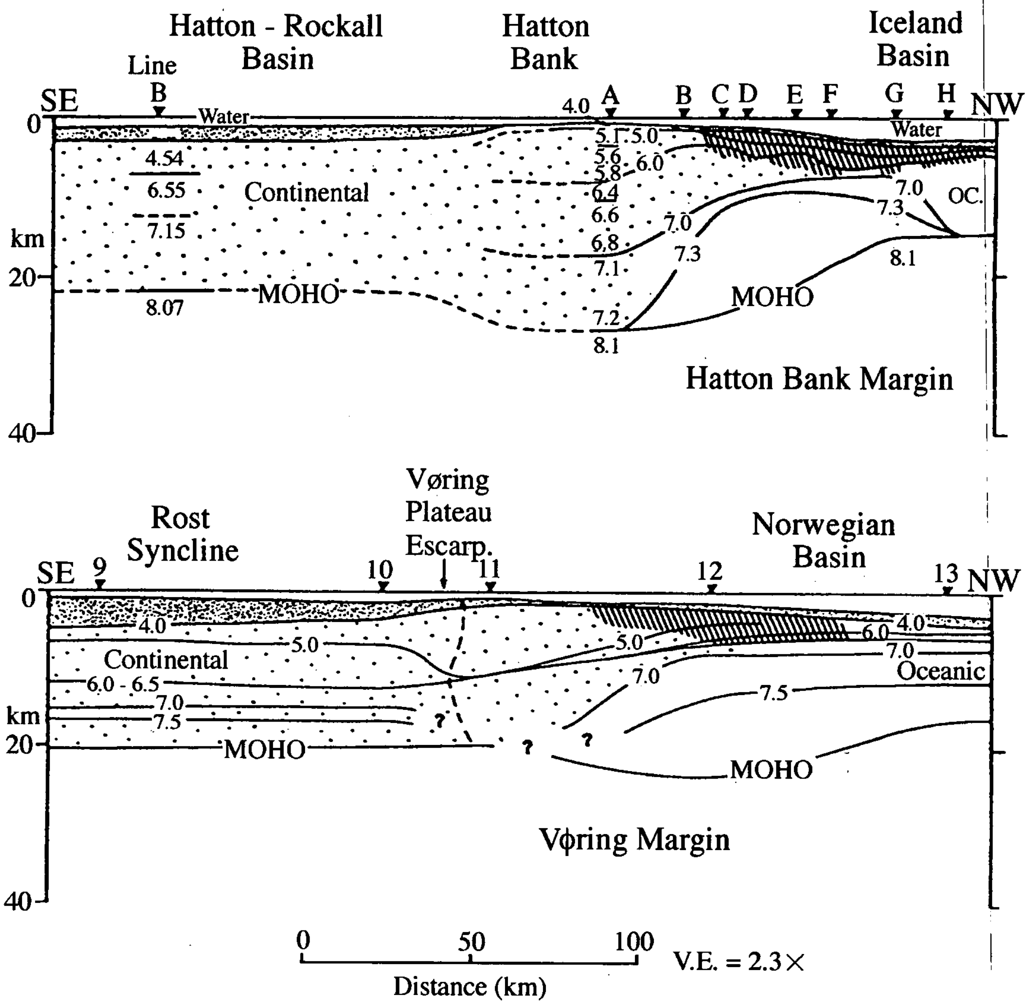


Fig. 5-1 Velocity structure across two volcanic margins.
From Morgan et al., 1989 (NARD-DPG Report)

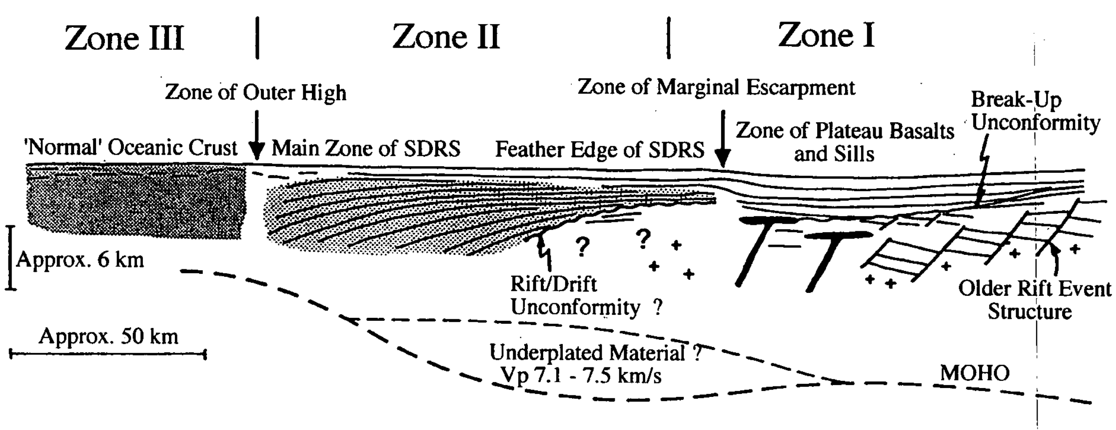


Fig. 5-2 Idealized zonation of a volcanic rifted margin. Zone I may develop a "sedimentary equivalent" to the zone II volcanic edifice and may, or may not, bered by older rift basins. If break-up takes place in a cratonic area like in SE Greenland, zone I may develop only very little or no pre- to sin-rift sediments and merely is a gentle basement arch. See also Fig. 5-3. From Morgan et al., 1989 (NARD-DPG Report)

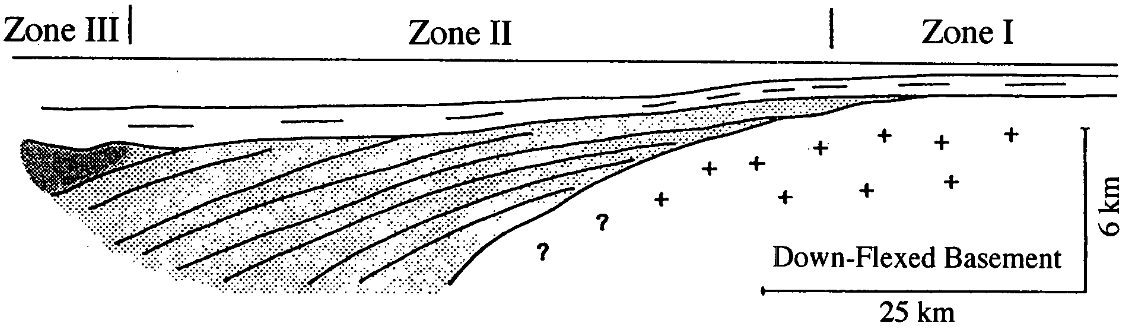


Fig. 5-3 Schematic cross section of a volcanic margin development in a cratonic area. However, some syn-breakup sediments are likely to occur between basement and onlapping SDRS wedge. Also some fault failure within the continental basement may occur although overshadowed by the significant flexural deformation. A CFB may build up within zone I. Note the differences from Fig. 5-2. Most real examples will show variations between these two different developments. From Morgan et al., 1989 (NARD-DPG Report)

Schematic Cross-Section of a SDRS Showing Generalized Stratigraphic Structure and Potential Stratigraphic Drilling Coverage

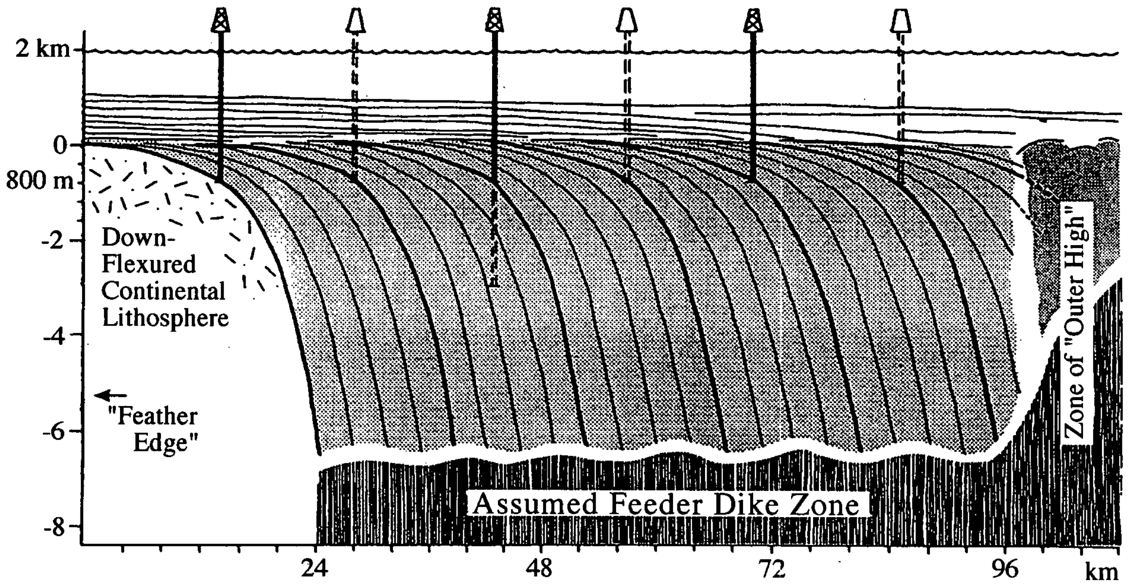


Fig. 5-4 Generic proposal to systematic sample the volcanic development of a volcanic rifted margin. The SDRS is assumed to consist of basaltic lavasequences deposted close to horizontal near sea-level. Their present dip (up to ca. 30°) is caused by rapid subsidence following extrusion. The transition into the feeder dike complex is believed to be fairly sharp. From Morgan et al., 1989 (NARD-DPG Report)

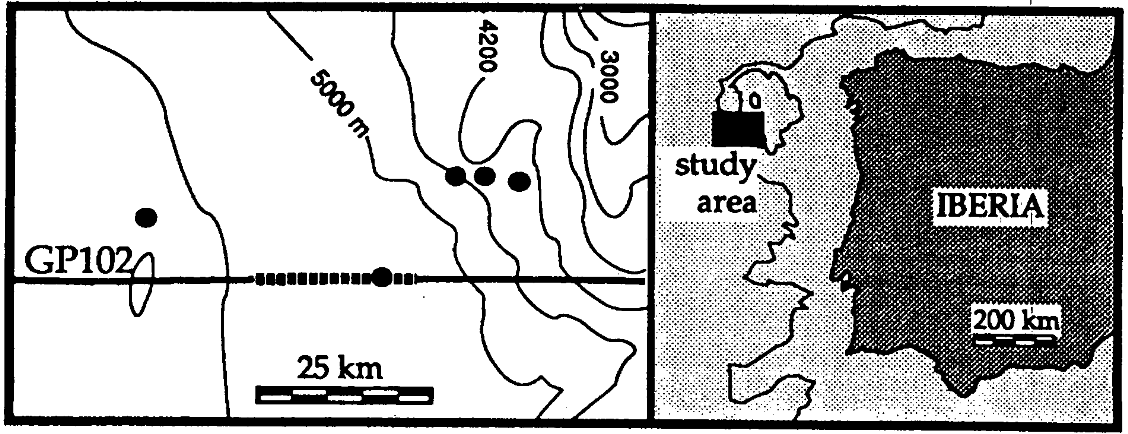


Fig. 6-1 Location of profile GP 102; Solid circles mark Ocean Drilling Program Leg 103 drillholes. Hoffmann & Reston, Dec. 1992, Geology

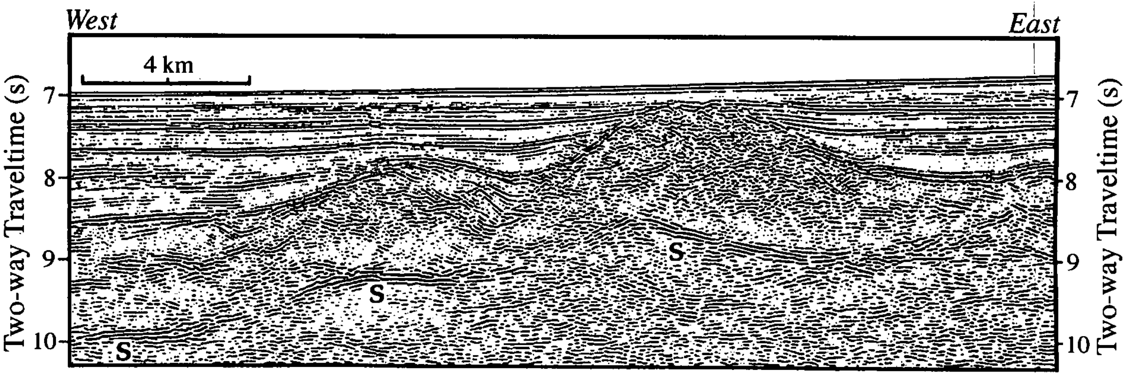


Fig. 6-2 Part of IFP (Institut français du Pétrole) profile GP102 after poststack time migration. S reflector is clearly imaged beneath titled fault blocks and appears offset. Note also that internal structure of fault blocks is unclear. Hoffmann & Reston, Dec. 1992, Geology

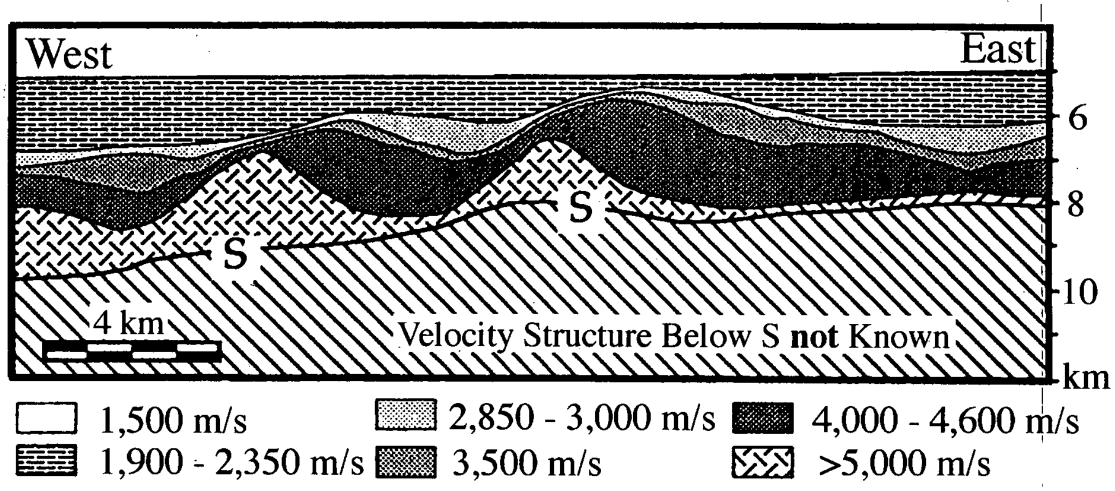


Fig. 6-3 Veolcity model derived from iterative prestack depth migration. Basic fault block pattern is apparent. Hoffmann & Reston, Dec. 1992, Geology

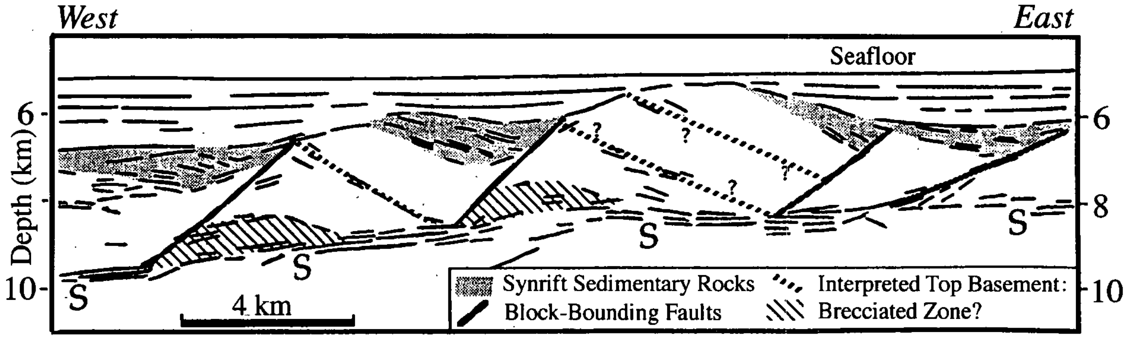


Fig. 6-4 Interpreted line drawing. Hoffmann & Reston, Dec. 1992, Geology

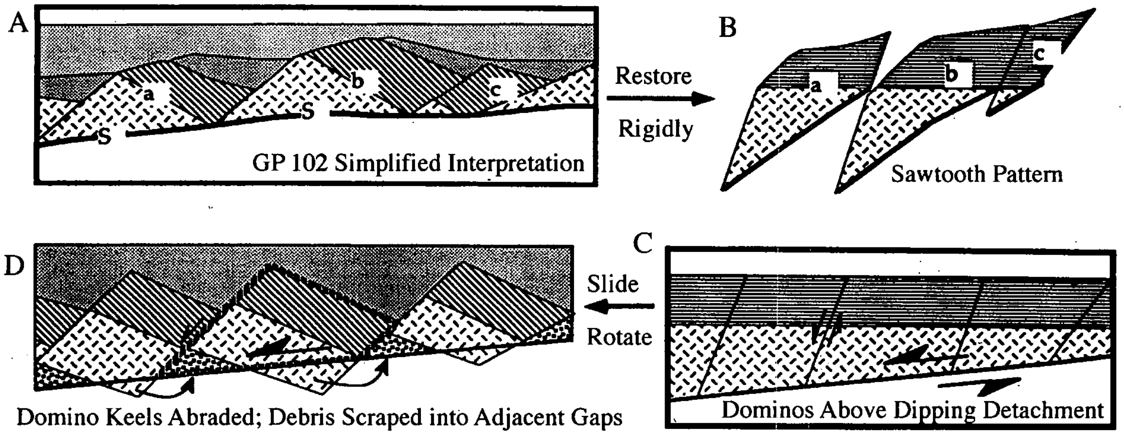


Fig. 6-5 Simplified interpretation of GP 102 (A) and rigidly restored section (B) showing space problem: base of blocks forms sawtooth pattern. Simplest way to overcome this problem is to modify base of fault blocks during extension and tilting. In domino model (C), space problem arises as blocks back otate (D). This can, however, be overcome if base of each block is cataclastically modified. Final fault-block shape (outlined by heavy broken line) is similar to that observed (compare D and A). Random dashes - basement; horizontal and tilted rules - prerift sequence; dots - synrift and postrift sequences. Hoffmann & Reston, Dec. 1992, Geology

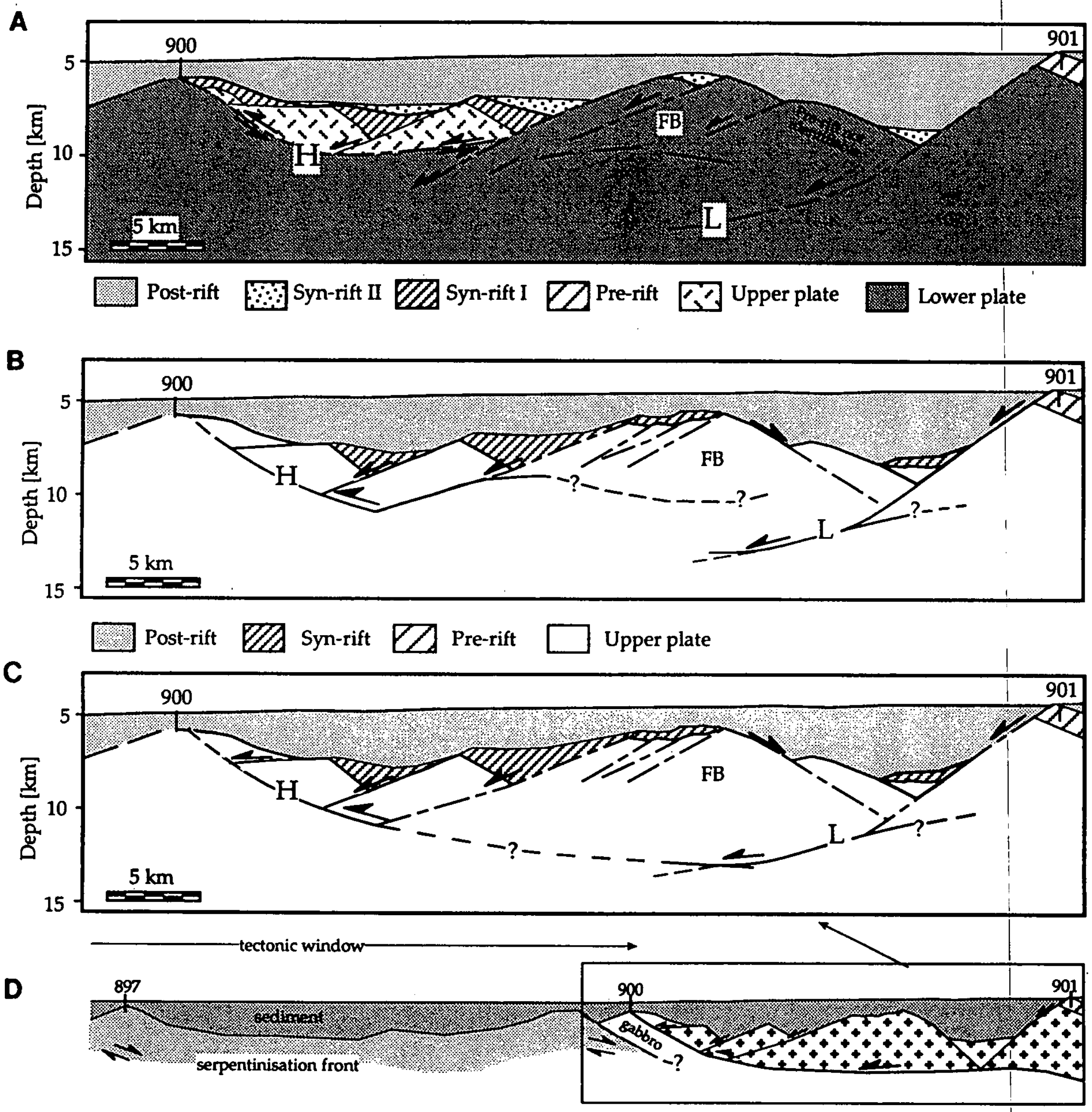


Fig. 6-6 Interpretations of the depth section of profile LG 12 between Sites 900 and 901. The eastern basement high is capped by a seismic trnsparent layer of prerift/pretilting sediments. Farther to the west, different tilted blocks are imaged. They are bound by fault structures (e.g., the listric structure L) and a detachment (H), which developed during different phases of rifting. **A.** H developed during the synrift I stage accommodating top-to-the-west motion, and was subsequently cut and rotated by L during the synrift II stage. Backrotation of H first during synrift I and subsequently during synrift II explains its current orientation. H terminates at the top of the basement high 500 m east of the drilled Site 900. Wedge-shaped sedimentary sequences are either of early synrift/prerift or of synrift II age. **B.** and **C.** Another interpretation involves H and L belonging to the same (C) or to the same family (B) of detachments, where normal faults and tilted blocks of the margin are rooted. (C) assumes the eastward-dipping part of H cutting across L at about 12 km depth by analogy to the Galicia Margin (e.g., Boillot et al., in press). **D.** This panel summarizes and extends interpretations of (B) and (C); to the west: deep lithospheric levels were tectonically unroofed as a result of conjugate, lithospheric shear zone activity during rifting. Krawczyk et al., Leg 149 Sci. Results.

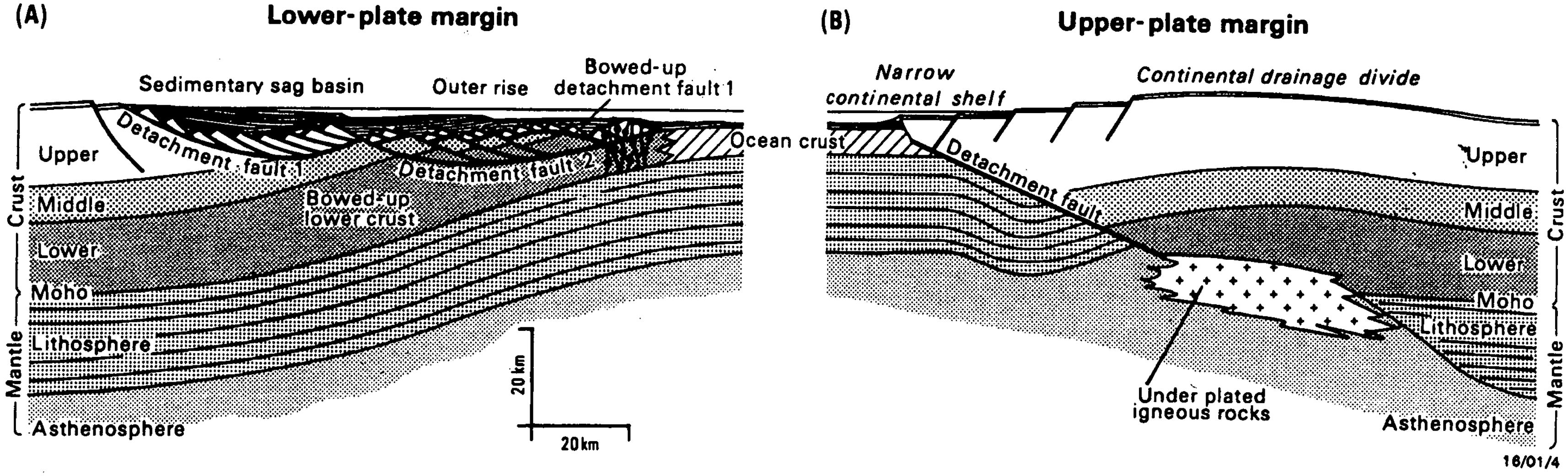


Fig. 7 Detachment-fault model of passive continental margins with lower-plate or upper-plate characteristics. Lower-plate margin (left) has complex structure; tilt blocks are remnants from upper plate, above bowed-up detachment faults. Multiple detachment has led to two generations of tilt blocks in diagram shown. Upper-plate margin (right) is relatively unstructured. Uplift of adjacent continent is caused by underplating of igneous rocks. Opposing passive margin pairs exhibit marked but complementary asymmetry. Lister et al., March 1986, Geology

Working Group 4 Report
Subduction and Earthquake Processes

Executive Summary

Working Group 4 ranked **Understanding Subduction Zone Earthquakes** as the highest priority for riser-based drilling. Despite the recent progress in this field, the physical and chemical processes that control earthquake nucleation and propagation remain unconstrained due to a lack of *in situ* measurements. Sampling of the seismogenic zone, and testing the many hypotheses for its behavior, requires deep drilling, almost certainly by riser-equipped deep ocean drilling vessel, because the seismogenic zone is principally a submarine feature. The ultimate goal is to fully understand the physical and chemical properties of the seismogenic fault zone, including the role of fluids, their variations through time and hence their relations to the seismic cycle. Active out-of-sequence thrusts which connects directly to the seismogenic plate boundary provide an important target for the use of the initial 2.5-3.0 km riser system.

Working Group 4 ranked **Understanding Magma Generation and the Growth of Continental Crust** as a second priority for riser-based drilling. The generation of arc magma and the formation continental crust are also important longer term consequences of subduction. One model for crustal formation suggests that arc crust forms the building blocks of continental crust and that arc crust has been produced globally since the Archean. This attractive model, however, remains unconstrained by quantitative studies of arc chemistry and needs to be tested by drilling through the fore-arc of an intra-oceanic juvenile arc. In addition, drilling into the middle crust of an arc to document its composition (e.g., tonalitic or basaltic) will potentially change our views on the birth of continents. Both fore-arc and middle crust sites are accessible with the design of the initial riser system.

Introduction

Plate tectonics represents the most fundamental geologic process on Earth and most Earth scientists agree that the driving force for plate tectonics is the excess density of the lithosphere in subduction zones. Sinking of the lithosphere in subduction zones pulls the plates apart at mid-ocean ridges which, in turn, results in the formation of new oceanic crust and lithosphere. Subduction is also associated with the largest instantaneous energy-release events on our planet (i.e., earthquakes) and it controls the chemical differentiation of earth's interior, eventually leading to the formation of continental crust. CONCORD Working Group 4 (consisting of 35 participants) recognized the fundamental importance of subduction zones and formed two subgroups:

(1) the dynamics of subduction zone earthquakes and
(2) the initiation of subduction and the birth of the continents.

The reports from these two subgroups, including the rationale for riser-equipped deep-sea drilling, are presented below.

Dynamics of Subduction Zone Earthquakes

Background

Most of the world's great earthquakes occur along subducting plate boundaries and record thrust displacements. The portion of the plate contact that slips during the earthquake is called the seismogenic zone and represents a significant portion of the shallow plate boundary. Understanding the seismogenic zone is of great societal relevance in developing a capability to mitigate damage from earthquakes, and this objective provides fundamental scientific and technological challenges.

During the past several decades, improved understanding of the kinematics of convergent plate boundaries has led to important long term probabilistic forecasts of earthquake occurrences. In contrast, the physical and chemical processes that control earthquake nucleation and rupture propagation within these fault zones remain unconstrained due to a lack of *in situ* measurements. Untested laboratory and theoretically based hypotheses abound in the geological and geophysical literature. Most of our knowledge of the physical conditions within the seismogenic zone has been inferred because we have never had the capabilities to sample the rocks and fluids from the fault zone. Sampling of the seismogenic zone, and testing the many hypotheses for its behavior, requires deep drilling, almost certainly by riser-equipped deep ocean drilling vessel, because the seismogenic zone is principally a submarine feature.

The CONCORD drilling program can achieve the goal of sampling the seismogenic zone by conducting *in situ* measurements, sampling, and long-term fault zone monitoring, perhaps to depths up to 10 km. Such a project has the potential to revolutionize the understanding of earthquakes by obtaining direct observations on the composition and mechanical properties of fault zone rocks and fluids, the nature of the stresses responsible for earthquakes, the role of fluids in controlling earthquake recurrence, and the physics of earthquake rupture nucleation and propagation.

Because the subduction zone thrust is shallowly dipping and emerges at the surface, it is accessible to study by a combination of techniques - geophysical imaging, marine-based riser drilling and long-term monitoring. These thrust fault zones involve thick intervals of rock and sediment on the plate that undergoes compaction, lithification, and dehydration reactions during transport from the deep-sea trench to the seismogenic zone.

The 1995 International Lithosphere Program workshop on "Dynamics of Lithosphere" and the 1997 SEIZE (Seismogenic Zone Experiment) meeting reviewed the progress achieved in recent studies on convergent margins. These meetings developed an international research program to study the seismogenic zone at convergent margins (Fig. 1). Here we report the results of the subsequent CONCORD workshop in 1997 to outline scientific drilling objectives for the OD21 riser drilling program.

Questions to be Answered

Drilling into the seismogenic zone of an active subduction plate boundary addresses the complete lack of data available on the fundamental physical and chemical processes which control earthquake nucleation and rupture in this zone. In general, the questions to be answered by the proposed experiment can be accomplished through:

- Sampling rocks and fluids from the seismogenic zone,
- Determining the fluid pressure, state of stress, active chemical processes and the physical state of the seismogenic zone, and
- Monitoring variations in fluid pressure, fluid chemistry and crustal deformation through time.

Sampling

By coring through seismogenic fault zones, it is possible to answer questions such as:

- ***What is the composition of the rocks in the fault zone?*** For example, what are the percentages of various clays, zeolites and other alteration products and how are these alteration products distributed through the fault zone?
- ***What are the deformation microstructures associated with faulting and strain localization in the fault zone?*** - A related question is to determine how important are chemical interactions in controlling fault zone rheology?
- ***How do the physical properties of fault zone rocks differ from the surrounding crust?*** - For example, what are the P- and S-wave velocities, electrical resistivity, density, porosity, pore compressibility, permeability, etc. of core samples exhumed from the fault zone?
- ***What are the constitutive properties of the fault zone?*** Specifically, what are the strength and frictional properties of recovered fault rocks at *in situ* conditions of stress, fluid pressure, fluid chemistry and temperature?
- ***What is the bulk chemistry of fault zone fluids and gases?*** In particular, what do the oxygen, hydrogen, helium and strontium isotopic compositions indicate about the origins of fault zone fluids?

Downhole Measurements

After drilling and coring through the seismogenic fault zone, a broad suite of downhole measurements are needed to answer questions such as:

- ***What is the fluid pressure and permeability within and adjacent to the fault zone?*** For example, is the fault zone overpressured, does the pore pressure vary temporally and spatially and can fluids permeate along or across the fault zone?
- ***How do stress orientation and magnitude vary across the fault zone?*** For example, are stress orientations and magnitudes continuous across the fault zone or do they vary in a

manner predicted by a variety of theoretical models depending on variations in physical properties?

- ***What are the in situ physical properties of fault zone materials and country rock?*** In particular, how are these properties related to the larger scale properties of the fault zone as determined by geophysical measurements?

Long-Term Monitoring

Finally, deployment of a suite of instruments in the boreholes to measure near-field seismic radiation, crustal strain, pore pressure, temperature, etc. over time, it will be possible to answer questions related to:

- ***Are fluid pressures in the fault zone constant or do they vary through time?*** For example, what are the possible roles of variations of fluid pressure in rupture nucleation and seismic cycle?
- ***Is fluid chemistry in the fault zone constant over time or are there variations that correlate with the seismic cycle?***
- ***How is the fault zone loaded over time?*** - For example, how does strain accumulation occur and is it affected by slip on deeper, aseismic segments of the master décollement as well as by slip on secondary faults near the main seismogenic thrust?

Experimental Design and Site Selection

The design of a riser-based drilling experiment into the seismogenic zone should include four phases:

(1) assembly of a comprehensive background data base not involving new drilling;
(2) a pilot program of JR-type drilling;
(3) riser drilling at water depths of approximately 2.5 km and 4.0 km;
(4) long-term monitoring of the deep boreholes.

Background information in advance of the riser drilling experiments should include several types of data. It will be vital to document patterns of seismicity accurately from ocean bottom seismometers (OBS) networks; particularly important will be segmentation of seismicity along strike and updip/downdip limits of the seismogenic zone. Control of regional uplift and crustal deformation patterns needs to be established from onshore Global Positioning System (GPS) and related geodetic studies. Surveys of near-surface heat flow are needed to establish regional variations in the thermal regime. High-quality swath mapping of the seafloor must be completed on a regional scale to document the morphology of both the incoming subducting plate and the forearc. High-quality seismic reflection profiles are needed to generate clear images of the plate boundary fault (décollement) and structural architecture of the upper plate, including out-of-sequence faults. The seismic reflection program should include 3D surveys of the anticipated riser-drilling targets. We need to take full advantage of existing "reference sites" from previous ODP drilling near the toe of the subduction zone and outboard of the subduction front. This information should include regional (strike-parallel) variations in lithostratigraphy, mineral assemblages, physical properties, results from earlier downhole measurements and logging, and a database of fluid-rock geochemistry. Background information should be supplemented from studies of nearby onland exposures of exhumed analogues; these comparative studies will help show relations among 3D geometry of paleothermal structure, spatial gradients in products of fluid-rock interaction, and structural architecture over ranges of P-T conditions similar to what we anticipate within the seismogenic zone. Predictions of hydrologic behavior should be derived from an iterative program of numerical simulations. Finally, a program of laboratory experiments should be started to demonstrate how given mineral assemblages are likely to react over the ranges of P-T conditions associated with the deep drilling program.

Because of the complexity of the seismogenic-zone experiment, and uncertainties in where the up-dip limit of the seismogenic zone might be located, it will be important to complete a pilot program of conventional JR-type drilling near the anticipated riser-drilling sites. A transect of holes should be designed to intersect a variety of structural targets at intermediate water depths (2,000-5,000 m) and intermediate sub-bottom depths (500-1,500 m). Particularly important targets will be seismically active out-of-sequence faults that appear to merge into the plate boundary fault at greater depths. Studies of these faults, which themselves may be seismogenic, will provide valuable information about hydrogeochemical behavior, changes in structural fabrics and physical properties, and rock alteration/diagenesis. The program of pilot drilling also should include a full suite of downhole measurements, in situ fluid sampling, and borehole monitors of fluid pressure, temperature, etc. Some of the pilot holes also could be used for installation of borehole seismometers.

Decisions regarding the locations of primary riser-drilling sites will require a trade off between the imposed limits on water depth during phase-one of the riser program, the landward dip of plate boundary fault, and thermal regime. Drilling in shallower water means that the décollement target depth will increase. Excellent targets are available, however, in approximately 2.5 km of water depth. A borehole could be positioned, for example, to take advantage of an intersection of an out-of-sequence thrust above the décollement. Ideally, such a borehole would then penetrate the décollement. When phase-two drilling become a reality, water depths will be extended to 4.0 km. Sub-bottom target depths during both phases of riser drilling will be 4-6 km, depending on the heat flow and structural considerations of the specific sites.

The anticipated temperature range at the bottom of the hole will be 200-250°C; selection of examples with relatively high heat flow will decrease the drilling depth. The coring program upon intersection of the décollement should include multiple fault zone intersections by deviated drilling, each with a different orientation. Because of uncertainties regarding the updip limit of the seismogenic zone, the riser-drilling site should be located conservatively, well downdip of the anticipated seaward seismogenic limit. Casing should be perforated within the fault zone and other favorable targets for long-term monitoring. A full suite of downhole measurements will include logging, temperature probe, packer tests, and measurements of electromagnetic potential.

Anticipated lithologies will include mostly sandstone and shale, but for non-accretionary margins, could also include basalt. Hydrocarbons are possible, but should be small in quantities; most subduction margins contain rocks with poor source-bed potential, low total organic carbon (TOC), terrigenous organic matter, and structurally dismembered reservoirs. Gas hydrates might be encountered at shallow depths but should pose no serious safety problems. Pristine pore fluids will be important for studies of fluid-rock interaction and fluid migration.

The long-term monitoring program should concentrate on the active plate-boundary fault zone, but should also include reference stations within the upper and lower fault blocks. Experiments should focus on: variability in temperature, changes in fluid composition, and changes in fluid pressure.

Technological Requirements

Technological developments will be critical for obtaining important data on the temporal relations between stress, strain, and pore fluid composition and, hence, on the relations between fluctuations in these properties and the earthquake cycle. The technological requirements have to be considered for:

(1) drilling and coring,
(2) *in situ* measurement during and shortly after drilling, including cuttings and drilling fluids analysis, and
(3) continuous borehole monitoring

More detailed discussions of the technological requirements for bore hole measurements and monitoring are in the report from Working Group 5.

(1) Technological Requirements for Drilling and Coring

The site for riser-based drilling of a deep hole through the seismogenic zone will be chosen on the basis of:

(a) results from drilling a transect of holes through the décollement and an out-of-sequence thrust with the JOIDES Resolution (JR); optimal core recovery in a variety of lithologies from clay-rich to sandy sediments, with occasional calcareous sediments, will be essential; and

(b) a 3-D geophysical characterization which provides the capability to extrapolate from the borehole through the seismogenic zone. To establish the steady state hydrologic conditions and monitor real-time subsurface transient events recorded by temperature, pressure and pore fluid composition anomalies, these boreholes will have to be hydrologically sealed, corked, and instrumented. A new generation of CORKs, easily wireline and submersible accessible, will allow emplacement and periodic replacement of recording instrument. The requirements for RISER drilling are deep penetration (4-7 km) through the seismogenic zone, subducted sediments, and ca. 500m into basement. Pressures may be in excess of lithostatic. The same sediment lithologies plus oceanic basement will be encountered, with maximum formation temperatures of 200°-250° C.

Additional technological requirements are: optimal core recovery in all lithologies, and the capacity to perforate the casing and isolate critical intervals at any depth for long range sampling and monitoring, and *in situ* experiments. Deviation and multiple penetration through some critical intervals are desirable.

(2) Technological Requirements for in-situ Measurements During and shortly after Drilling

Being able to reliably measure in-situ temperature, pore pressure, permeability and stress, and to recover pristine (uncontaminated) pore fluids is essential. In addition, vertical seismic profile (VSP) experiments are necessary to calibrate seismic data, and both wireline logging and logging-while-drilling (LWD) will be necessary in the JR holes.

(3) *In Situ* Monitoring

*** In Borehole Monitoring:**

By drilling into the seismogenic zone, critical data on temperature, pore pressure, strain, stress and pore fluid composition will be obtained. For short and long term monitoring (weeks to years) of these physical and chemical properties, existing and newly developed devices, sensors or samplers will be emplaced in the RISER deep borehole, including a seismometer. They will record in these properties in real time fluctuations throughout an earthquake cycle.

Pre-, co-, and post-seismic signals of variations in temperature, pressure, pore fluid composition, strain and stress will provide very important insights on the relationships between the physics and chemistry of the seismogenic regime and earthquake processes. The fluid osmo-samplers will continuously collect pristine fluids not only from the seismogenic zone, but also from additional critical perforated isolated intervals (one per interval). Fluid samplers emplaced at shallow depths will be connected with a hydrologic string that will be accessible at the seafloor by submersible or remotely operated vehicle (ROV). At deeper levels, including the seismogenic zone, intervals of perforated or screened casing will permit emplacement of fluid samplers and other devices. Their recovery would require a ship with re-entry capabilities. The borehole should be left accessible for future, new innovative experiments.

* **At the seafloor**

Seismicity, seafloor deformation (geodesy), heat flow and fluid composition will be monitored adjacent to the drill-hole on the seafloor. An array of fluid osmo-samplers will be deployed for continuously monitoring and sampling focused and diffuse fluid flow rates and composition.

Infrastructure requirements

Riser-based drilling to considerable depth (> 2-3 km) will take many, probably up to 18 months or more. Since multiple scientific targets are proposed the personnel in the drill-site scientific team is likely to change and therefore there must be good communication between all members of the changing scientific teams (e.g., between the land- and sea-based personnel).

In addition, communication links among the following scientific programs is essential:

1. Land- and marine-based GPS studies
2. Detailed seismic network programs
3. Submarine geophysical programs, including 3-D seismic reflection studies, refraction programs, heat flow and seafloor temperature measurements

International Collaborations:

The scientific questions outlined above cover some of the most fundamental problems in the earth sciences and require collaborations with a range of international communities. Present relevant programs include:

International Continental Drilling Program (ICDP)
Margins
Seismogenic Zone Experiment (SEIZE)
Oil industry
Japanese-French Kaiko-Tokai Program

Subduction Initiation and Birth of the Continents

Background

Subduction of oceanic lithosphere controls the chemical differentiation of our planet by delivering water into the mantle which leads to melting, magma generation and volcanic eruptions. In addition, subduction reverses the chemical differentiation of the Earth by physically moving oceanic crust and sediments derived from erosion of the continents back into the mantle. This material may sink through the mantle to the core-mantle boundary where, ultimately, it may return to the Earth's surface as a hot, mantle-derived plume.

An additional important consequence of the volatile input to the mantle and the generation of arc magma is the formation of arc crust. One model for crustal formation suggests that arc crust forms the building blocks of continental crust and that it has been produced globally since the Archean. This attractive model, however, has been challenged by two issues:

(1) the bulk composition of the continental crust is andesitic (often composed of large tonalitic-granodioritic plutons), whereas the bulk composition of intra-oceanic arcs has been considered to be basaltic;
(2) juvenile arc crust recognized in the Phanerozoic is often boninitic in composition. Early Archean greenstone belts, however, typically lack boninites.

These controversies, therefore, raise significant doubts about the relation between arc magmatism and the growth of the continents. One solution to this problem, however, has recently been suggested by detailed seismic images of modern arcs which suggest that the middle crust of at least the Izu-Bonin arc is composed of a thick layer of tonalite, contradicting the conventional wisdom. This also raises a questions about the generation of tonalitic rocks in an island arc setting. Clearly, the study of arc processes, from subduction initiation to crustal evolution, will provide major breakthroughs in our understanding of continental crust genesis and crustal evolution throughout Earth's history.

Questions to be Addressed

Riser-based drilling of primitive, intra-oceanic arcs provide the opportunity to answer the following fundamental questions.

1. How are subduction zones initiated?
2. What is the bulk composition of juvenile island arc crust and how does this composition evolve through geologic time?
3. What is the relation between the evolution of arc crust and the growth of continental crust?
4. How do the igneous products of arc systems contribute to the mass balance and recycling of materials in subduction zones?

Subduction Initiation: Forearc crust is produced when subduction begins and hence is the only part of the arc system that preserves a record of this event. Understanding the composition of forearc crust is therefore fundamental to constraining physical models for the initiation of subduction zones .

Although various models have been proposed for the formation of forearcs, two end-member models have been recognized. One end-member argues that forearcs are composed of trapped, older arc or oceanic crust, whereas other models argue that forearc crust forms by a type of seafloor spreading during subduction initiation. Resolving this fundamental problem in planetary evolution requires drilling forearc crust to the Moho and hence requires oceanic, riser-based scientific drilling.

Composition and evolution of juvenile island arc crust: Arc magmatism may evolve due to progressive changes in the mantle wedge. This could reflect metasomatic enrichment due to flux from the subducted slab or depletion due to continued melt extraction. In order to understand this, we must have a record of the igneous products of an arc system. One strategy to obtain this record is through the study of wind-blow tephra. The prevailing wind direction over certain isolated intra-oceanic arc systems is predictable enough that tephra in sediments downwind from the arc system can be confidently inferred to have been derived exclusively from the system in question. The recovery of pelagic sedimentary sequences, from which such tephra can be isolated and analyzed, permits a history of explosive, subaerial volcanism for the arc system to be reconstructed. Riser drilling will allow thicker sequences proximal to the arc to be sampled, and thus provide better documentation of the changes through time in eruption frequency and magma composition.

Evolution of arc crust and the growth of continental crust: DSDP and ODP drilling have been essential for our understanding of how oceanic crust forms, and OD21 may provide similar advances for understanding continental crust formation. A model suggests that primitive arc crust is the fundamental 'building block' of continental crust, and that the continents form by the coalescence of arc and other oceanic terranes. This model is controversial because the bulk composition of the continental crust is andesitic, whereas the bulk composition of intra-oceanic arcs has been thought to be basaltic. Special processes, such as delamination of the lower continental crust, were thought necessary to reconcile this compositional variance. Recently, however, detailed seismic images of arc crust are interpreted as indicating that the middle crust of the Izu-Bonin arc may be composed of a thick layer of tonalite. If true, the bulk composition of juvenile arc crust approximates that of continental crust, obviating the need for processes like delamination. Drilling into the mid-crust of a juvenile arc would allow us to test these models and contribute in a fundamental way to our understanding of how Earth's continental crust is produced.

Mass balance and recycling of island arc materials in subduction zones: Convergent margins provide one of the most important chemical buffering systems on the planet, exerting important controls on the composition of the Earth's atmosphere, hydrosphere, lithosphere and mantle. This process also controls the rate at which new continental crust is produced. Since none of these processes have been quantified, an important scientific objective is to produce quantitative mass balances for subduction and magma generation in island arcs.

Experimental Design

In order to test the above scientific questions, it is necessary to determine geophysical and fluid properties of crustal sections resulting from both initial subduction and mature arc magmatism. A possible drilling program would consist of three general sites.

1) Outer Forearc High (typically 2,500 m water depth and <200°C).
2) Island Arc Crust (typically 1,500 m water depth and ~300°C).
3) Rifted Backarc Margins (typically 4,000 m water depth and low geothermal gradients)

Data collection during drilling will include coring, logging, fluid sampling, geophysical experiments (VSP, tomography, electromagnetic experiments). Legacy holes will be available for long-term monitoring use.

Technological Requirements

Hole stability and penetration depth require riser capability. Arc hole will require high temperature logging. Fluid and biological contamination will be issues common to all deep holes.

Infrastructure Requirements

In addition to detailed crustal velocity structure images, 3D seismic reflection profiling, long-offset seismic reflection, conductivity structure and seismicity study are required. Extensive study of spacial distribution of rock types and their geochronology are essential to interpret the drilling results within a broad context of arc evolution.

In the case of northern Izu-Bonin arc, detailed crustal velocity structure image is available together with swath bathymetry, IZANAGI/SeaMarc sidescan image, submersible surveys and extensive collection of dredged rocks (JAMSTEC, ORI, GSJ and Moana Wave collections). Nine ODP sites provide basic information on seismic stratigraphy and arc evolution.

Exposed equivalent land sections at Ogasawara islands and Tanzawa-Izu Massif, although obliterated by later tectonic events, provide further background information.

Collaboration

Close coordination with U.S.MARGINS initiative will be required. It is hoped that other nations will develop similar initiatives to which collaboration can be directed.

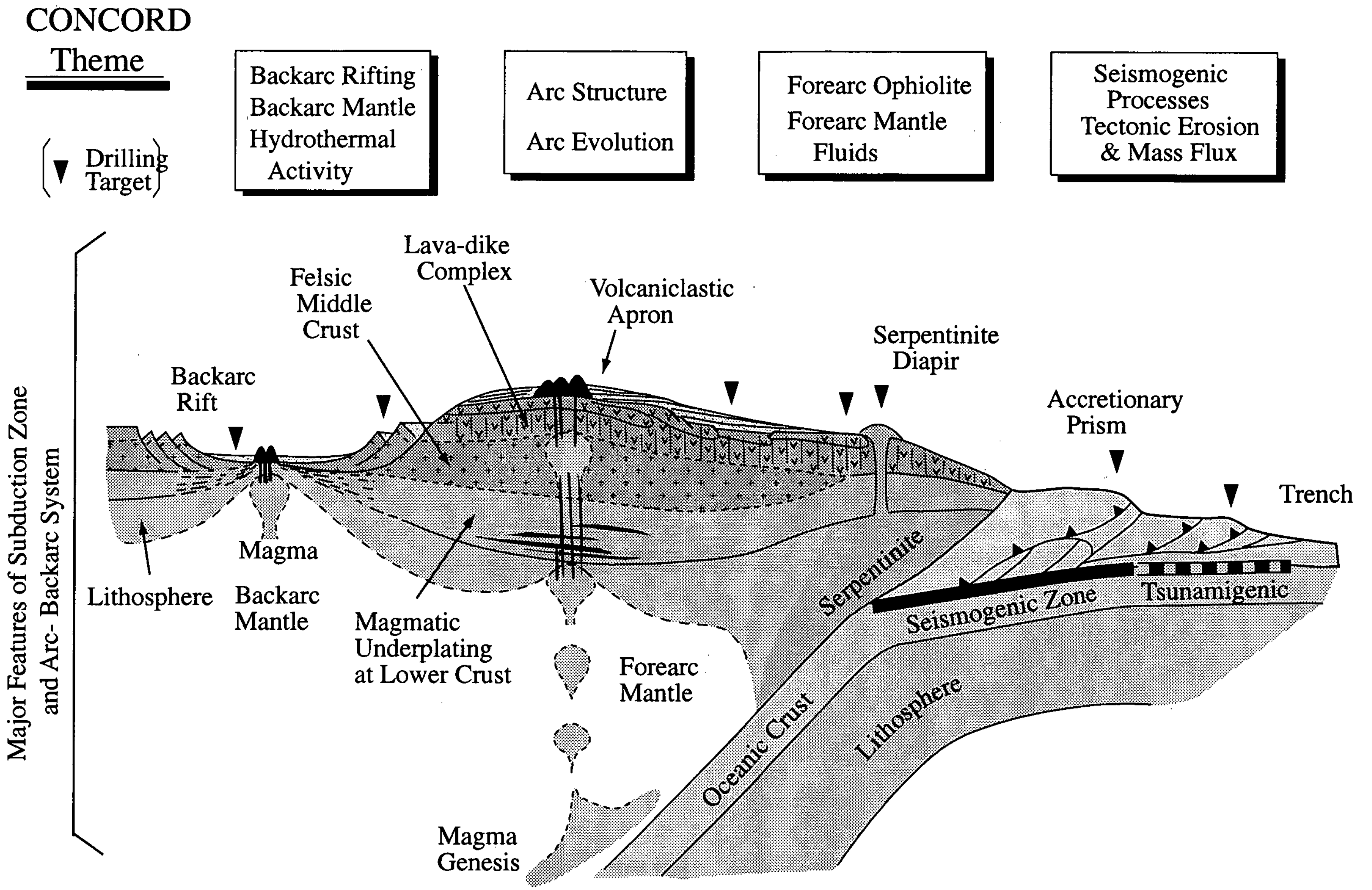


Fig. 1. A schematic cross-section of a subduction zone and arc system with major features and themes discussed by members of WG4. Four priority site of riser-based drilling are also shown.

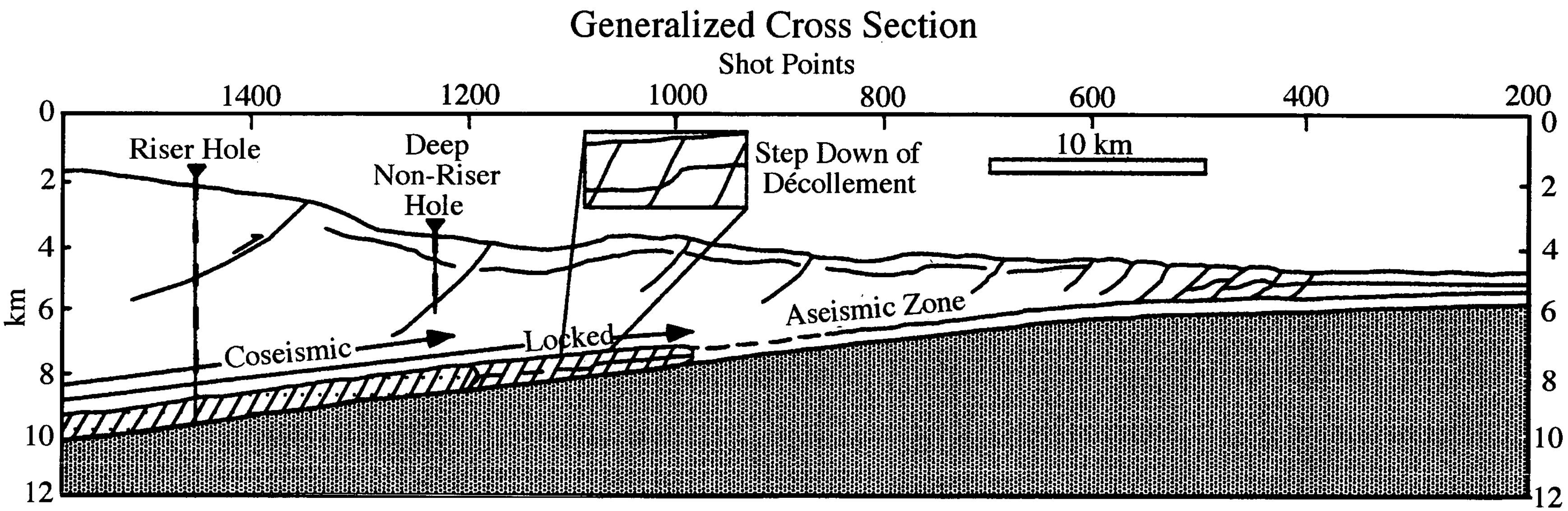


Fig. 2. Generalized cross-section of the frontal portion of a subduction zone showing the décollement, seismogenic zone and out-of-sequence thrust. The location of a proposed riser-based drilling site is indicated.

First Hole to Seismogenic Zone

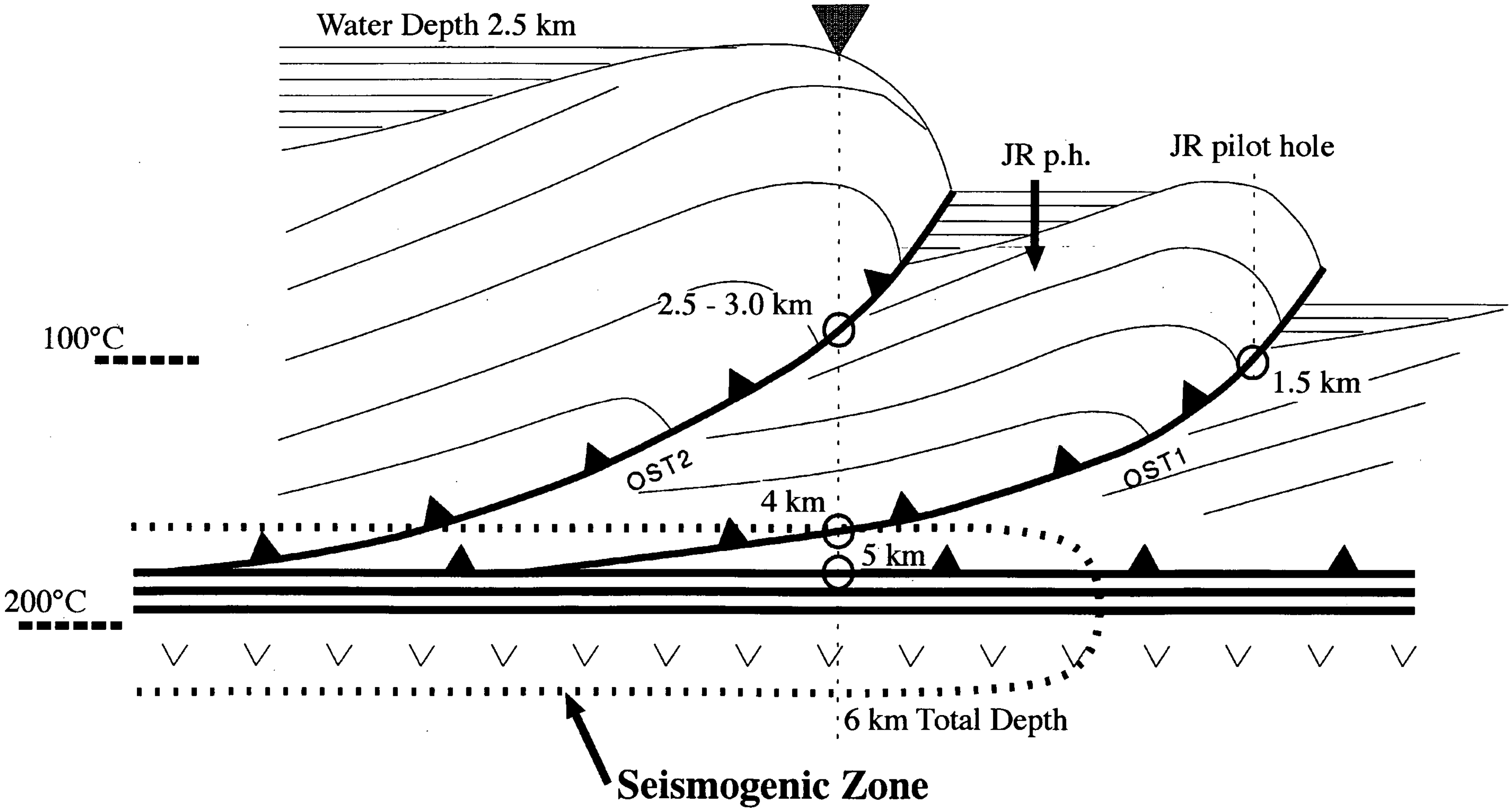


Fig. 3. Proposed plan for riser-based drilling into the seismogenic zone that also penetrates two out-of-sequence thrusts. Plans for supplementary JR pilot holes are also shown.

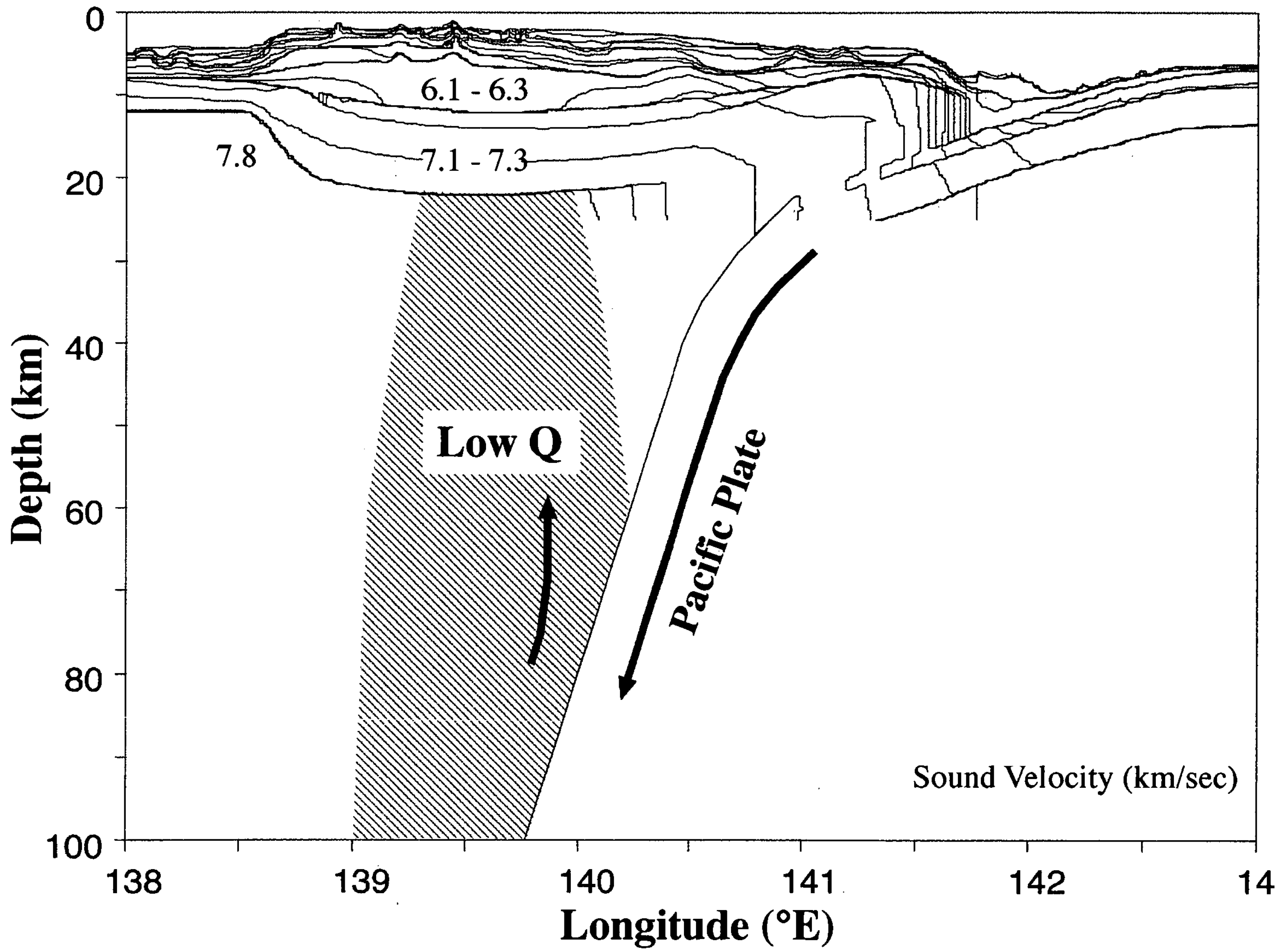
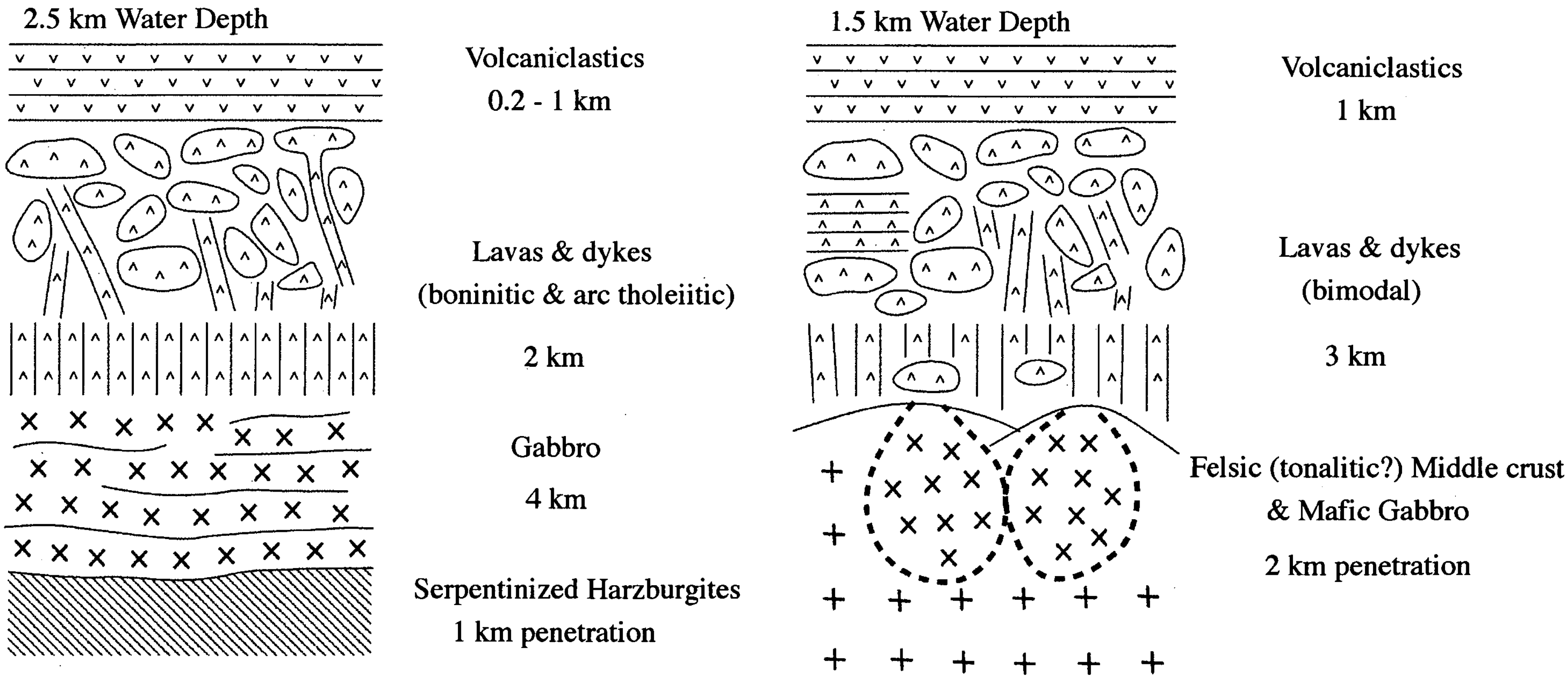


Fig. 4. Crustal cross-section of Northern Izu-Bonin arc as a generic example of an oceanic island arc system. Two generic riser-based drilling sites, one in the forearc an the other in the volcanic arc, are also indicated.



Outer Arc High = Testing Ophiolite Model & Initial Process of Subduction

Bulk Composition, Architecture & Felsic Middle Crust of Island = Subduction Factory

Fig. 5. Speculative lithologic interpretation of oceanic island arc section at two generic sites.

Working Group 5 Report
Borehole and Seafloor Observatories

Executive summary

Riser drilling will provide many new and exciting opportunities for short- and long-term observations of time-dependent deep sub-seafloor processes. Two main areas of experiments are discussed here: (1) Investigation of the seismogenic zone of a plate-boundary fault in an area of major seismicity; and (2) Exploration of hydrogeological processes in the deep sub-seafloor.

Monitoring the seismogenic zone along an active fault will allow, for the first time, in-situ observations of the various interdependent geological, geophysical and geochemical processes during the earthquake cycle. These observations are critical to the understanding of those properties of the earth's crust that change prior to, during, and after an earthquake. In particular, certain changes may precede rupture, and hence be useful in the field of earthquake prediction.

Riser drilling and borehole monitoring will also provide an opportunity to quantify and understand hydrogeological processes over a large range of depths and temperatures in the subseafloor. These new observations will allow validation of fluid flow models and a quantitative assessment of heat, fluid, chemical, and biologically-derived fluxes between the earth's crust and the ocean, and establishment of precise relationships between fluid flow and oceanic crust accretion, metallic ore generation, and sediment deformation.

Much of the basic technology for conducting borehole experiments in the seismogenic zone is presently available, although advances in high-temperature sensors, instrument packaging, and operational procedures need to be explored. The development of a multi-level multi-parameter hydrologic monitoring tool is proposed. One difficult technical capability that would be desirable would be the ability to drill multiple deviated satellite holes, so that multiple sensors could be emplaced at a given level of interest with a single deep riser hole. Another useful technical development would be a system to service and modify borehole observatories without return of the riser drill ship, to extract, repair, and install instrument strings. Finally, seafloor and borehole experiments carried out before, during, and after drilling, and the use of a conventional drilling vessel in combination with the riser ship, will need to be carefully coordinated so as to extract the most useful information from each drilling target.

<u>*Working Group 5 Report*</u>

Long-term in-situ Monitoring of the Seismogenic Zone

Background

Riser drilling will bring to the earth science community a unique opportunity to monitor closely "the earthquake cycle", because it opens the possibility of reaching the "seismogenic zone" at subduction plate boundaries where great thrust earthquakes occur. Within the seismogenic zone, inter-plate earthquakes take place at depths of several to tens of kilometers. These great earthquakes recur with a period of tens to hundreds of years, causing great life and property losses in populated areas. The spatial and temporal variations of stress and strain within the earthquake cycle are poorly understood, in part because there have been no direct observations of the process within a seismogenically active fault zone. Riser drilling, in combination with remote observations and seafloor and borehole experiments, will allow us to construct a four-dimensional understanding of the earthquake cycle within the seismogenic zone.

It is generally well accepted that some plate motion at seismically active plate boundaries is often accommodated by aseismic slip. In some areas, earthquake displacement accounts for only about 1/3 of the expected motion based on the known convergence rate. The time constant and the magnitude-frequency relationship of aseismic slip are not known, although understanding them is critical, for this process may drastically change the stress-strain field and play an important role in the earthquake cycle. We do not know how aseismic slip is related to the occurrence of major earthquakes. Recent numerical modeling predicts significant temporal change in intraplate stress field and quasi-stable sliding between and prior to major earthquakes, but this hypothesis remains untested. Fluids may also significantly change the stress-strain-strength field within and around the seismogenic zone, although quantitative relationships between fluid flow, fluid pressure, and seismicity are not well constrained. At subduction zones where background seismicity is high, such as in the Japan Trench area, we know that the rupture of large events often begins within one of many seismically active patches, possibly along fault asperities. Recent progress in rock mechanics has provided several explanations about which physical parameters control the nature of shear faulting. We must relate these parameters to direct observations, however, in order to identify which ones are most important for earthquake process.

Questions to be Addressed

1) How is the relative displacement between subducting and overriding plates accommodated other than by major interplate earthquakes? When, where, and how often do silent/slow earthquakes occur? Answers to these questions will have obvious implications for the physical nature of both inter- and intra-plate deformation, and will be important for understanding tsunamigenesis.
2) What are the physical, mechanical, and chemical properties of the plate boundary, and what changes occur through the earthquake cycle? This question relates directly to the deformation process, to the fundamental details of how earthquakes occur, and to how they might be predicted.
3) What is the nature and role of interplate fluid flow in seismicity and crustal deformation? Are fluid flow events or transient changes in pressure precursors to seismic activity? If so, can proxies be developed to allow remote monitoring of fluid pressure within plate boundary faults?

If we are to understand and possibly predict the occurrence of major subduction earthquakes, we must determine the nature of precursory events and processes. Such understanding will require:

(1) simultaneous monitoring of geophysical, geochemical, and hydrogeological parameters, and

(2) observational access to an active seismogenic zone. Riser drilling will provide the only opportunity to emplace borehole observatories at the depths of greatest interest.

Experiment Design

Key observations permitted by riser-drilled holes must be combined with seafloor observations to form a network for monitoring the seismogenic zone, and these observations must be linked to additional networks on land. Figure 1 shows an example observatory linking seafloor and borehole instruments. Long-term borehole observatories should provide key data for:

1) Mapping the spatial and temporal distribution of interplate events, including normal and slow earthquakes and creep.
   Required instruments: Broad-band seismometers for understanding the precise rupture process; strainmeters and tiltmeters to characterize continuous deformation and slow events.
2) Resolving temporal variations in stress, strain, and the pore pressure field and their interrelationships.
   Required instruments: Seismometer arrays to invert earthquake mechanisms for stress field, and to determine anisotropy related to geometry of pores and cracks; multi-packer hydrologic observatories to monitor changes in pressure.
3) Determining temporal variations in physical properties within the fault zone.
   Required instruments: Seismometer array across the fault to monitor trapped waves; borehole logging to determine initial in-situ properties; multi-packer observatories to monitor pressure.
4) Detecting temporal variations in fluid flow.
   Required instruments: Multi-packer observatories to monitor pressure and temperature; fluid sampling to study geochemical signatures; electro-magnetic (EM) measurements as a possible proxy for fluid flow.

Holes used for most of these objectives need to intersect the seismogenic zone, although it would also be interesting and useful to penetrate the fault within the tsunamigenic zone (shallower and seaward from the seismogenic zone). Clearly, detailed site surveys will be necessary for proper placement of any deep hole. There must be continuous coring through the fault zone, and at least spot coring through the overlying sediments. Periodic sediment temperature measurements to determine thermal conditions, and sediment/fluid sampling for chemistry, will also be important for documentation of in-situ conditions. It would also be desirable to measure formation pressures periodically with depth, using a push-in probe. The full depth to the fault zone should be logged continuously (probably via logging-while-drilling) prior to casing. Most sensors and samplers will not require permanent installation, but strain meters and broadband seismometers will need to be maintained over decades in open (uncased) holes. Thus it will be necessary to decide in advance which instruments will be installed. It appears that at least two kinds of holes are required for these experiments:

(1) one which provides an open section at the bottom in which strain meters and broadband

seismometers can be cemented in place, with cables extending to the seafloor for data recording and telemetry; and

(2) one which is cased and fully cemented, and perforated within zones of interest, with individual zones isolated by packers and instrumented.

For the first type of hole, the diameters of the final casing and the open hole at the bottom need to be large enough to accept the instruments that are to be cemented in place. A hydrophone or hydrophone array hanging in the hole above the cemented instruments could allow repeated VSP and cross-hole seismic experiments. These holes containing broadband seismometers and strain meters need not be drilled to the total depth of the seismogenic zone. For the second type of hole, casing would be installed through the fault zone, with multiple intervals perforated and tested. Formation fluid pressures and least principal stress could be measured through perforations, and fluid samples could be drawn from the formation following extraction of drilling fluid (perhaps using the assistance of a gas lift or other standard oilfield method). Instruments would then be installed between mechanical or hydraulic packers that would isolate individual perforated depth intervals to monitor pressure, temperature, seismic signals, and tilt, and to sample fluids continuously or periodically. Biological substrates could also be installed within these isolated intervals, and retrieved later along with fluid samples. If permeability is to be measured, it will probably also be necessary to install wire-wrapped, pre-perforated screens, as perforations through casing made after casing installation may not provide sufficient permeability and allow adequate hole development prior to testing. Perhaps screens with a preinstalled gravel or sand pack could be used, to allow filtering of fine-grained material prior to packer testing. In addition to single-hole experiments and observations, there would be much gained through multi-hole experiments. Cross-hole tomography could allow characterization of lateral properties and variability. Geochemical flow experiments could be accomplished through injection of a conservative tracer in one hole (up gradient) and measuring the arrival of this tracer in another (down gradient). Similarly, cross-hole hydrogeological experiments would allow aquifer-scale properties to be determined. This would be best accomplished through generation of excess pressure in one hole, and monitoring of pressure changes within a second. The spacing between these holes will be an important consideration, and will best be determined through analysis of expected properties and in-situ conditions. Greater distances will require larger source signals and greater time for propagation (in the case of aquifer tests), but will have the advantage of averaging over larger sections of the formation. A two-hole spacing of 500 m might be appropriate for the first set of experiments. Perhaps the most logical progression would be drilling of one or more relatively shallow holes for emplacement of broadband seismometers and strain meters, followed by drilling of a deep hole intended for geological, geophysical, and hydrogeological characterization of the fault zone. In the long term, one or more additional deep holes might be drilled as well, allowing cross-hole experiments at depth, although this effort would need to be justified by results of the initial experiment. Another interesting option would be drilling deviated holes, perhaps two or more originating from a single initial casing string, in which observational instruments could be emplaced.

Technological Developments

Much of the basic technology for conducting the seismogenic zone experiment is presently available, although packaging and deployment methods need to be explored. In addition, some instruments have temperature and pressure limitations that might be extended to improve flexibility. Special casing emplacement and instrument installation methods also may need to be developed to allow a small number of holes to be used for multiple purposes (see discussion below). Specific technological developments that would be of use in the proposed experiments include:

1) Strain meters and broadband seismometers that can work above 60°C and at high pressures, with minimal maintenance requirements;
2) Fiber-optic temperature measurement instruments with resolution ≤ 0.1°C and range of 0-200°C;
3) Ability to drill multiple deviated holes from a single initial hole, to assist with emplacement of multiple instrument strings (with different completion requirements) and cross-hole experiments without requiring use of a riser for more than one deep hole;
4) Real-time data acquisition and instrument control to allow rapid interpretation of seismic data and to allow more rapid sampling during seismogenic events;
5) Ability to service and modify borehole observatories (extract, repair, install instrument strings) without return of the riser drill ship.

Ocean Hydrogeology

Background

Considerable progress has been made in sub-seafloor hydrogeological studies with the capabilities of the *JOIDES Resolution* using core data, drillstring packers, and logging tools for formation characterization, probes pushed ahead of the drill-bit for obtaining "snapshots" of thermal structure and obtaining fluid samples, and "CORK" instrumented casing seals for long-term observations in the upper oceanic crust or in shallow parts of continental margins. Current scientific ocean drilling technology does not permit drilling and direct observations of hydrogeological processes operating at great depth in the oceanic crust or continental margins, however. A major expectation from riser drilling is to be able to quantify and monitor hydrogeological processes in some detail over a large depth interval of the subseafloor. This will allow fluid flow models to be validated, heat, fluid and chemical budgets to be assessed, biological activity to be investigated, and the relationships between fluid flow and oceanic crust accretion, metallic ore generation, and sediment deformation to be more precisely established.

Hydrogeology of the Oceanic Crust

A very general understanding of the hydrology of the uppermost part of the oceanic crust is beginning to emerge as a result of detailed seismic, heat flow, and geochemical surveys, shallow drilling at a few ridge-flank locations, and a single hole penetrating to a substantial depth of 2 km below the top of the igneous crust. The structure that has emerged is to first order a layered one, comprising a discontinuous to continuous sedimentary blanket, a highly permeable extrusive igneous layer, and a relatively low-permeability lower crust. Relative to the extrusive igneous layer, where fluids are driven at high volumetric rates (meters to tens of meters per year) by thermal buoyancy forces, marine sediments are characterized by permeabilities lower than those of the upper igneous crust by orders of magnitude; where sediments accumulate to form a continuous blanket, they confine the upper igneous crustal aquifer and reduce or make insignificant the exchange of fluids between the oceanic crust and overlying water column. In areas where there are high-temperature sources of heat, at volcanically active seamounts and mid-ocean ridges for example, the presence of sediment can insulate the crust and focus discharge, favoring the formation of large ore deposits. Beyond this, our understanding of crustal fluid flow is very rudimentary. Some outstanding questions can be addressed with existing drilling technology, but many cannot, and will require riser drilling capabilities. This is true for studies that require penetration and recovery of the upper igneous crustal section, which is by nature highly incompetent and unstable, and it is certainly true for any attempts to drill deep into the igneous crust.

Questions to be Addressed

Some of the more important questions that remain unanswered about ocean-crustal hydrothermal circulation that can be addressed only by riser drilling and deep borehole monitoring are:

1) How is permeability distributed in the extrusive igneous crust? How much of the total interstitial volume involved in fluid flow, and what are the implications for water/rock reactions?
2) To what depth does thermally and geochemically significant fluid flow penetrate into the lower crust?
3) How does the hydrology of the oceanic crust change as the crust ages? How isolated does the crust ultimately become?
4) Do major normal faults play an important role hydrogeologically in ridge-flank environments?

Answering these questions with riser drilling and borehole monitoring, and combining the answers with others gained from future seafloor and shallow drilling studies, will allow a major advance to be made towards understanding quantitatively the hydrology of a vast part of our planet, where water is believed to flow very freely, and is probably stored in great quantities. This understanding is critical for assessing global heat and geochemical budgets, and determining fluid residence times in contrasting parts of the earth where they may range from less than one year to more than 100 million years.

Hydrogeology of Continental Margins

Both passive and convergent continental margins are loci of pore-water flow and expulsion. At passive margins, flow is probably dominated by movement along stratigraphic aquifers, driven by hydrostatic heads from terrestrial recharge areas. At convergent margins, tectonic forces cause migration and expulsion of pore fluids by reduction of porosity and thickening of the sedimentary load. In addition, fluids are generated by dehydration, transformation, and dissolution of hydrous materials. At both types of margins, fluids play a critical role in being a main coupling agent between tectonic, petrologic, and chemical processes. Hence, the understanding of hydrogeologic processes is a major goal of any comprehensive study on continental margins.

Questions to be Addressed

At ***Active Margins*** (both accreting and non-accreting):

1) What are possible sources of fluids (e.g. mineral dehydration, magmatic, buried seawater) that flow through the accreted and subducted sediments, as well as basement rock at convergent margins?
2) What is the extent of mass and heat redistribution caused by fluid flow through convergent margin systems?

3) Is flow through the convergent margin system compartmentalized, and if so, what constitutes the compartment boundaries?
4) Is flow controlled by thin focused permeable zones, or is it pervasive and diffuse throughout the sediments and basement rocks?
5) What is the relationship between earthquake activity and changes in temperature, pore pressure, fluid expulsion, and fluid compositions? Can these changes be used to predict earthquakes?

At ***Passive Margins***:

1) What is the extent and volume of topographically driven flow from the continents to the ocean?
2) What is the depth distribution and the extent of deep diagenetic and metamorphic reactions and how do these reactions influence the rheology of the sediments?
3) How do short-term events, such as slumping and variations in sea surface level (e.g. tides, waves, sea level change), influence flow?

Experiment Design: A New Multi-Level Multi-Parameter Hydrologic Monitoring/ Testing/Sampling System

Understanding steady-state and transient hydrogeological processes in any environment requires knowledge of permeability, pressure, temperature, fluid chemistry, and rock composition. Because drilling and fluid circulation creates a major hydrologic disturbance, borehole monitoring is required to enable undisturbed conditions of pressure, temperature, and fluid chemistry to be determined at depth by allowing time for natural conditions to be re-established. Continuous long-term monitoring also allows natural temporal variations of these parameters to be observed, such as those that may be associated with tectonic or volcanic events, earth tides, and ocean tides. In order to determine vertical variations of properties and processes, monitoring must be made at multiple depth intervals.

One great advantage of riser drilling which can be used towards this end is the ability to emplace sophisticated casing strings, similar to those used in detailed hydrological studies on land, that would allow multiple intervals to be isolated, sampled, and monitored. A major development associated with riser drilling should be a system to do this. A conceptual sketch of a single node of such a system is shown in Figure 2. Sensor strings, and the positioning of monitoring intervals must be designed according to the particular details of the hydrologic lithology encountered. This would be determined by coring, logging, and packer observations. As many nodes as necessary or possible could be established based on the nature of hydro-lithology and technical limitations.

A sequence of operations for the deployment of a multi-level monitoring system would be as follows: Casing would be run in, cemented, and perforated. The multi-packer sub-casing would then be installed and set with the riser rig on site. The instrument string could be deployed, recovered, serviced, and/or re-deployed at any time with or without the drilling vessel. The inside diameter of instrument sub-casing would be made as large as possible to allow other instruments to be deployed at non-node positions or even in open hole below casing. Provision would be made to accommodate microbiological experiments such as in situ colonization and enrichments experiments using incubation chambers mated to ports to selectively grow different classes of microbes for later microbiological analysis and identification by DNA sequencing. Microbiological experiments would greatly benefit from the knowledge of the temperature, pressure and fluid chemistry conditions that would be recorded simultaneously(see WG-I rept).

Severe limitations will be set on monitoring instrumentation by temperature, particularly near ridge crests but also deep in accretionary prisms, seismogenic zones and oceanic crust. It will be important to place temperature-sensitive components as shallow in the holes as possible, possibly at the sea-floor. Obtaining pristine pore fluids from great depths with riser drilling will be challenging, and may require development of techniques to clean the formation of infiltrated drilling mud prior to sampling. One possible solution is through cyclical pumping, although use of continuous fluid samplers and/or in-situ fluid analyzers would allow chemical recovery from drilling-induced disturbance to be tracked.

Ideally, hydrogeological monitoring should be planned at all deep holes to establish base-line information about steady and transient hydrologic conditions in a wide variety of settings. Best use of the holes for both specific experiments and base-line studies would be made with multi-level monitoring systems that would be designed with the goals discussed above in mind:

1) The number of isolated sampling/monitoring intervals should be maximized to provide the greatest spatial resolution of chemical and physical gradients.
2) The internal diameter of the multi-packer sub-casing should be maximized to permit passage of the greatest number of tools and sensors.
3) Once the multi-packer sub-casing is installed and set, the formation should remain isolated from the hole at all times, irrespective of whether sensors and samplers are in place at access ports.
4) Any instrument string inside the sub-casing should be removable and replaceable by wireline or submersible.
5) It would be highly desirable to access ports in a "logging" mode (using a single tool deployed by wireline) as well as a continuous-monitoring mode (with multiple long-term sensors).

Infrastructure and collaborations

Deployment, servicing, and upgrading borehole observatories will clearly require long-term commitments for international collaboration such as through ION. Data dissemination and archiving are another major issue for international cooperation. Links should be established with other national or international initiatives for borehole monitoring. Without appropriate infrastructure in place, the goals of this WG will become difficult to reach.

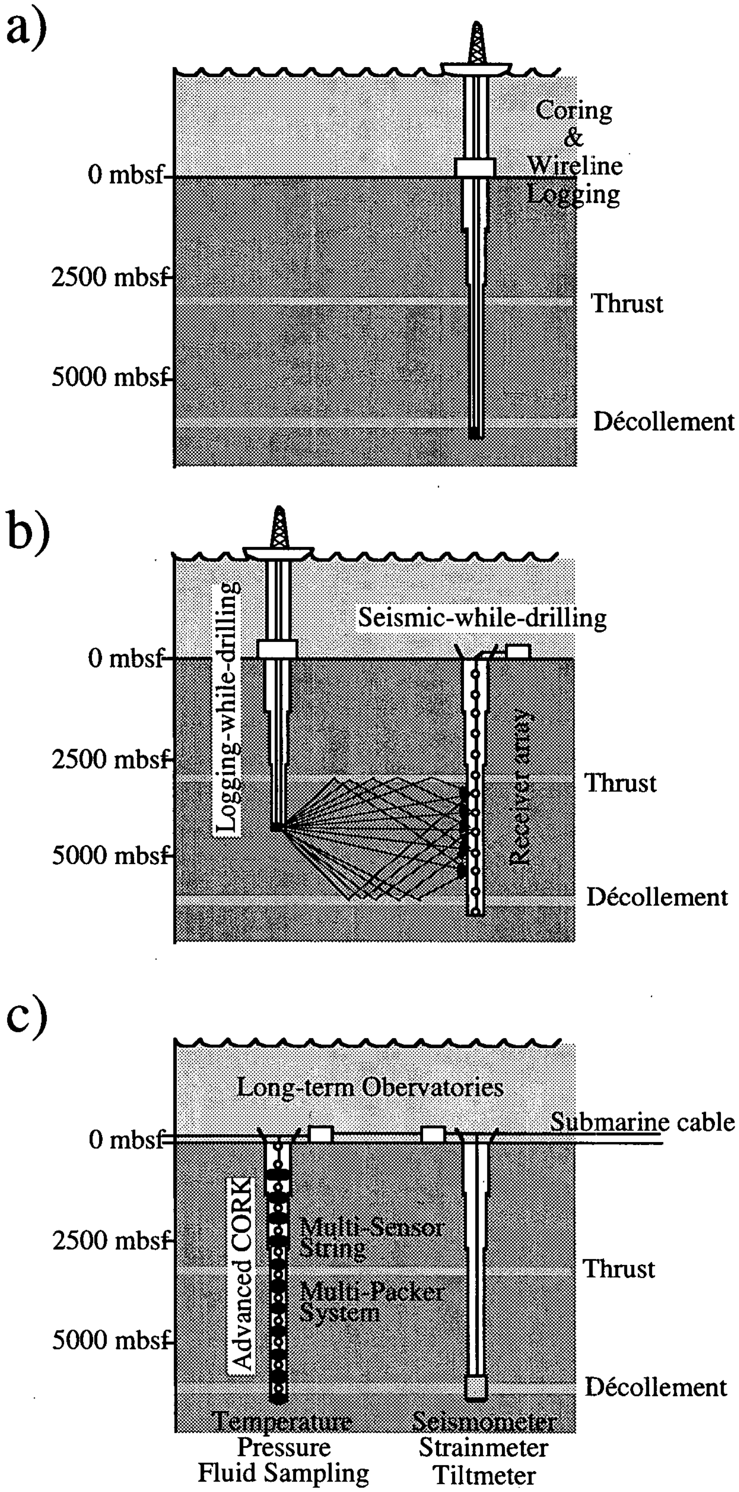


Fig. 1 Operational procedure to construct long-term observatories. a) Coring and deployment of wireline logging in the first hole. b) Deployment of logging-while-drilling and seismic-while-drilling into the second hole after the installation of a receiver hydrophone array into the first hole. c) Installation of broad-band seismometer, strainmeter, and tiltmeter into the "seismic hole" and multi-packer system with removable multi-sensor string (temperature, pressure, and fluid sampling tool) into the "hydrologic hole".

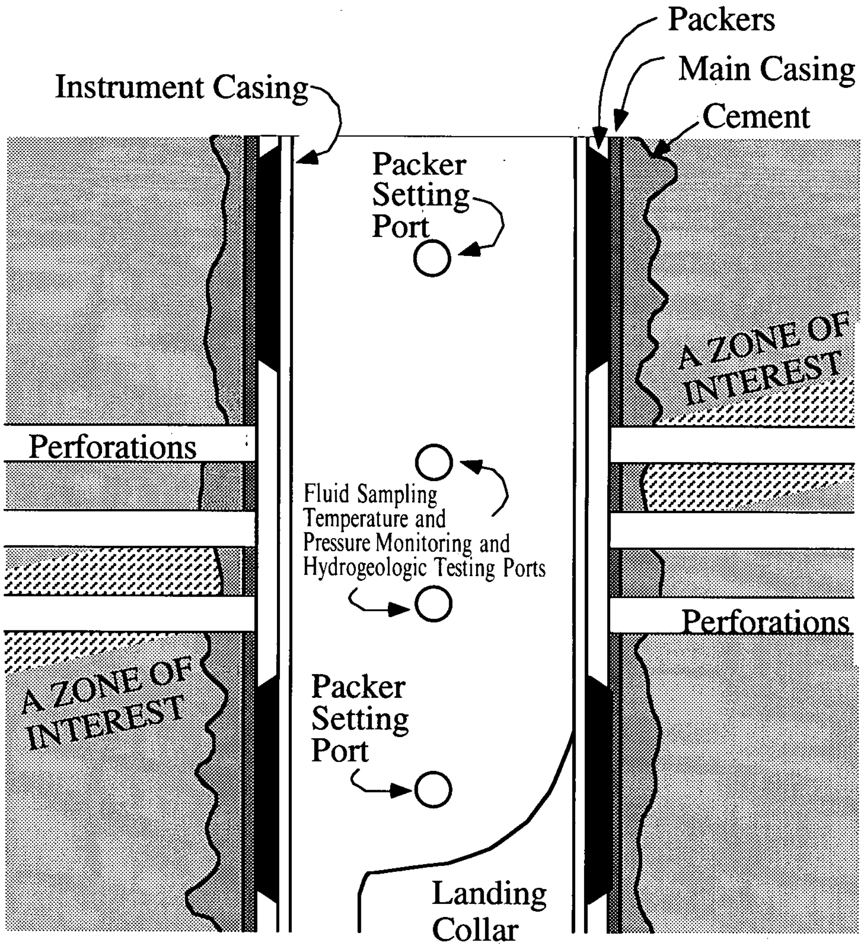


Fig. 2 Schematic illustration of a borehole depth interval isolated by packers for fluid sampling, temperature and pressure monitoring and hydrogeological tesing. Hydrogeologic properties are monitored at several depth intervals, using the multisensor tool.

Working Group 6 Report
Drilling and Tool Technology Development

Executive Summary

The members of CONCORD Working Group 6 (**Drilling and Tool Technology Development**) attended as observers and consultants to all scientific working groups (1-5) and met as a group in order to consolidate the requirements for Riser Supported Deep Ocean Drilling in the 21st Century. The division of the expertise of WG6 to this task was related to the scientific topics being discussed.

There was a clear consensus in all the scientific groups that **a riser supported drilling vessel** with a **drillstring capability longer than that available within the present ODP** program is necessary; numerous questions were asked regarding the operational capabilities and constraints for using such a vessel.

This report provides the background information to the proposal for a Riser-Equipped Deep Ocean Drilling Vessel, the types of equipment which it will employ, and the anticipated benefits which will accrue to science. **Advanced and new technologies will have to be developed to meet the announced scientific requirements**, and different techniques may have to be employed for sampling in order to obtain maximum benefits from this new vessel. The support of other vessels to drill pilot holes needs to be considered. The **development of technology for the new riser vessel should be carried out in conjunction with industry and the international scientific community.**

Introduction

Working Group 6 (Drilling and Tool Technology Development) was composed of 23 members. As well as having an international complement, the group encompassed members with different drilling, coring and operational experience in industrial and scientific drilling.

The report summarizes the proposal for a Riser-Equipped Deep Ocean Drilling Vessel, and then makes comments on aspects of the vessel, its capabilities, and aspirations of the scientists who wish to use the vessel, as summarized within the five scientific working groups at the CONCORD meeting.

No comment is made in this report on the technology which will be required to develop the suites of downhole instruments for monitoring of legacy boreholes or for the re-entry systems with which it will be necessary to equip those boreholes for drillship and other platform intervention. However, it is noted that there is a requirement to ensure that the drilling vessel carries sufficient winch and wireline capacity for initial deployment of such tools, and that there are no undue restrictions to downhole instrument design which may be caused by the riser/BOP installation on the borehole.

OD21 Preliminary Engineering Development

a) General Concepts

Current ODP technology allows drilling with a drillstring and bottom hole assembly to a total depth capability (ship to bottom of hole) of 7,500 m. In order to progress the borehole, circulation to seabed is maintained with seawater supplemented by drilling mud (seawater plus various additives), and casing may be installed if the formation is weak or long term operations are planned for the borehole. Re-entry to boreholes can be pre-planned or carried out during drilling and is frequently successful, even in uncased or partially cased boreholes. Problems occurring as a result of unstable geological formations are remedied with the normal drilling operations of hole cleaning, setting of casing from the top to below the difficult formation, and by the addition of various fluids and powders to the seawater to make a more viscous/higher specific gravity circulating fluid to remove cuttings and fill fractures. With these methods, cuttings and mud residues are deposited on the sea floor; this may cause environmental harm in the quantities which could be produced from the drilling of a very deep borehole.

Preliminary planning of the technology envisaged for the new Riser-Equipped Deep Ocean Drilling Vessel (**Figure 1**) will allow longer string lengths, a mud re-circulation system, and a pressure control system (Blow-Out Prevention). This riser-equipped drilling system (**Figure 2**) will provide more secure borehole control in water depths to 4,000 m and a total string length of 12,000 m.

b) Riser Construction and Development

The construction and development of the OD21 Scientific Ocean Drilling System Riser is planned to be divided into two phases:

The First Phase; A 2,500 m water depth (Class) riser drilling capability, where the nominal riser diameter is 16" with 2,500 m length and BOP. The completion of this first phase construction and development is planned for the year 2003. The Riser Class 2,500 m specifies a design criteria which may, under certain conditions, allow operation in up to 3,000m water depth.

The Second Phase; 4,000 m water depth (Class) riser drilling capability, the development of which will be concurrent with initial ship operations.

This two-phase approach allows a number of operational benefits at the same time as the scientific community comes to terms with the different sampling and data handling methodology which will be necessary for both deep boreholes and riser drilling operations.

From the technology viewpoint the use of a 2,500 m Class riser will allow essential operational experience and feedback into a design for a 4,000 m Class riser system. Additionally, using the period of technology advance between now and the time when a deeper water riser needs to be fabricated allows for incorporation of all new technology which may become available through present commercial deepwater drilling operations and international research into materials and methods. Utilizing these technologies may involve holding another "International workshop on riser technology" similar to that held at Yokohama, Japan, in 1996, before the second phase of final design and construction takes place. In any event, the drilling vessel construction shall allow for consideration of a 4,000 m Class conventional oilfield riser from the outset. This meets many of the objectives of the science working groups at CONCORD, and will allow for further development of riser extension for the future.

The Benefits of Riser Drilling

a) General

* Riser Drilling is a method which allows **deep** drilling into the ocean seafloor in areas of scientific interest, irrespective of the nature of that seafloor

* It has the potential to reach presently unachievable, or difficult to achieve, goals of the international scientific community

* It provides increased safety, once the Riser/BOP has been installed

Present ODP operations allow only poor borehole control. They cannot effectively lift cuttings from a deep penetration borehole, even with the circulation to seabed of expensive drilling muds which, when using the open-hole method of drilling, have also to be environmentally acceptable discharges.

Similarly the present drilling methods are also unsuited to coring in overpressured formations, where there is the potential of a blowout. A riser will greatly assist operations with an ability to deploy various selections of borehole stabilizing fluids (muds).

However, riser drilling with or without BOP requires the first part of the hole (200 - 800 meters of section from seabed dependent on the lithology) to be drilled in a similar manner to present ODP operations, in order to make a hole deep enough to secure the conductor casing and riser/BOP assemblies.

b) Once Riser or Riser/BOP is installed

* A Riser and BOP installation provide the potential for better borehole stability

* Deeper penetration, even in critical pressure regimes

* Fewer problems due to pipe sticking, quicker hole re-entry, good depth reference

* Better core recovery due to improved borehole conditions

* Possibility for horizontal/directional drilling and coring

* More extensive logging of borehole with better depth control:
    a) Mud circulation gives cuttings, fluids and gas for analysis even if no core.
    b) Range of wireline tools can be increased
* Contamination of the seafloor environment can be minimized
* Deeper, legacy boreholes should be possible

Due to the re-circulation of the drilling fluid, rock cuttings can be recovered on the ship, and the formation conditions can be monitored by analyzing these cuttings even in the absence of core samples. This is especially important in deeper boreholes, where rock mechanics may preclude the cutting of routine cores. Additionally, the re-circulated fluid carries information on the formation gasses which can also be analyzed.

Wireline logging runs will be carried out after drilling but prior to setting casing. The tools will be run in the riser and previously set casing strings, therefore they are not limited to an outside diameter of less than the inside diameter of the drillpipe, as in present ODP operations.

As the finished hole is armored by a casing, it becomes a legacy hole which is less prone to collapse. Thus, it can be used for long-term monitoring, for a variety of scientific purposes.

Technology Issues Arising from the Scientific Working Groups

From the discussion within the CONCORD scientific working groups, it was clear that it will be necessary to inform the scientific community in more detail about the methodology and procedures involved with mud re-circulation and riser type drilling in order to extract the best quality of data at all stages during the drilling of the borehole. It must also be stated that **controlled drilling progress is essential, especially at greater depth,** if the borehole is to remain in good condition and available for post drilling scientific investigations. This could mean that the rate of borehole penetration may be slowed down in places, casings may have to be set at non-optimum scientific depths, and sub-sampling while drilling may have to be modified from an originally planned program.

Mud Circulation and the use of a Riser

Figure 3 illustrates the concept of drilling a deep borehole using a step-by-step approach. The initial steps are similar to that presently undertaken in the existing ODP drilling program with the "JOIDES Resolution".

The benefits of "Mud Circulation" have long been recognized in the drilling industry as an aid to borehole stability; it is now a commonly used, but very sophisticated, technology in the oil and gas drilling industry.

For scientific drilling, this technology is a key to satisfying the scientists' requirement for deep penetration boreholes and at the same time supplying information which may otherwise not be available. The drilling fluid (commonly called "mud") forms a "mud cake" on the wall of the borehole, or invades a poorly consolidated zone. This allows for better borehole stability before any casings are set, by keeping the borehole wall from collapsing.

The mud properties can be varied to suit borehole conditions, and also continuously carry information to the surface by way of rock cuttings, dissolved gas and fluid chemistry. This allows information to be obtained from the borehole, even if no core can be recovered. The mud also serves to control borehole pressure in conjunction with the riser and the Blow Out Preventer (BOP). As the mud has to return to the surface for repeated circulation, there must be a return path of mud between the surface and the seafloor. This return path is the "Riser". The conventional type of the riser used in oil industry is a pipe, enclosing a drill string inside the pipe as shown in **Figure 2**. The benefits of using the riser have already been noted in this report..

Figure 3 also indicates that, in the scheme of riser drilling, casings have to be set at various intervals in order for the drilling to progress with the borehole remaining stable. This casing program is an important element of the drilling program. The intention is to leave the cased borehole in a condition suitable for borehole monitoring for many years into the future.

In the first stage, drilling/coring is done in a similar manner to that carried out with the "JOIDES Resolution", using APC, XCB or RCB, without riser/BOP. Wireline logging then needs to be completed after coring and before any casing. The procedure for riser/BOP installation is then as follows:

1. A conductor casing and wellhead are secured to the seafloor.
2. Drilling without coring is carried out until the depth of the pilot hole is reached, and a second casing is set and cemented at this depth.
3. A riser and BOP may then be connected to the wellhead, and recirculation drilling and coring can be done followed by wireline logging in the newly opened borehole.
4. The new hole section is then enlarged (hole opening) and a further casing is inserted and cemented.
5. The process is repeated until the hole objectives are reached.
6. When the Total Depth (TD) has been reached, and all wireline logs are completed, a liner is set to the base of the borehole, thus securing the borehole for long-term monitoring and scientific experiments.

Note: The top of the "Casing" is on the seafloor, and the top of "Liner" is a little above the bottom of the preceding casing.

Shallow Gas Problem

In unconsolidated formations, or those with very low geotechnical strengths it is not possible to install a riser/BOP system until a considerable depth into the formation has been drilled. This can be a depth of 200 ~ 800 m in order to obtain the security for the wellhead assembly, casing and riser tension. All of this may mean that a riser and BOP cannot be installed without penetrating through an area in which shallow gas may be present.

Figure 4 shows an accepted industry method for dealing with the shallow gas problem. It is preceded by extensive geophysical surveys to determine the optimum, gas-free site, and is then further controlled by the initial pilot drilling and Remotely Operated Vehicle (ROV) observations while this is being done. If gas is encountered, the drilling is stopped, the pilot hole is cemented, and a new pilot hole is drilled at another location.

If gas is not detected, then the borehole proceeds to a point where wellhead and casing are set and further drilling/coring with a riser and BOP may be done.

Such drilling procedures will require a new set of guidelines to be drawn up for the safe working operations of OD21.

Drilling into High Temperature Zones such as Zero Age Oceanic Crust

Zones anticipated to have very high temperatures (several hundred degrees Celsius) cause problems both to drilling and logging tools. Because it is necessary to cool down the borehole in these instances to allow tool operation (see **Figure 5** for tool operating temperatures), large volumes of cooling fluids, possibly seawater, are required and can be supplied in a fashion similar to that shown in **Figure 6**.

The anticipated procedure to drill/core into such high temperature areas is as follows;

(1) Set Hard-Rock Guide Base on the seafloor

(2) Using the standard method of hard-rock drilling technology of the present ODP-JOIDES Resolution drilling, a few hundred meter drilling/coring are done.

(3) Hammer-In Casing technology now under development by ODP may be used to set casing to the same depth already cored by procedures (1) through (2). If it is not available, a well head and casing shall be set and cemented to the same depth by conventional methods.

(4) Riser is connected to the well head. The riser has a BOP-like block on the bottom of the pipe. This block is to eject returning seawater and cuttings to the seafloor.

A riser is still used in order to effect bit and tool exchange quickly and allow larger diameter logging strings.

Logging Tools

Many kinds of wireline logging tools are now available from oil industry developments and all of them can be applied to the OD21 riser drilling concept.

Mixed tool assemblies are also available, for example the MDT (Modular Formation Dynamic Tester) which measures temperature and pressure and can collect formation water samples. The water samplers have sensors to detect the entrance (pollution) of mud water. Thus, there is an opportunity to take unpolluted water samples from the formations while logging.

The wireline logging tools are temperature limited. Present limitations for routine tools are normally 175°C or less for continuous use, and up to 200°C for a short time. Some higher temperature tools are already developed, allowing operations routinely in 230°C-260°C, for geothermal drilling and the KTB deep borehole.

The importance of the use of combination logging tools in deep-hole drilling cannot be over-emphasized, as it is important to minimize wireline logging trips and thus preserve maximum borehole stability.

Horizontal/Directional drilling/Coring

After finishing the borehole, deviated drilling/coring is also available in the cased, riser-drilled borehole. This technology is already routine in oil industry applications, and in scientific boreholes will allow 3D experiments.

By window cutting the casing at pre-determined depths, or by projecting from the base of the borehole, it will be possible to drill short or long holes at an angle to the main borehole in order to conduct experiments or obtain different subsamples of core.

Downhole motor technology and core barrels/sampling devices will need to be designed in order to take advantage of this new development in scientific drilling opportunities.

Working Group 6 Report

Issues of Modification of Information and Contamination of Samples

The use of a riser introduces an increased risk of information modification and sample contamination, if compared to an open-hole drilled with seawater:

a) Magnetization of samples

Steel-encased boreholes and drilling with rotary bits in hard rock formations can induce artificial magnetic polarizations. Additionally, the running of the corebarrels by wireline causes similar fluctuations. These can be reduced and possibly overcome by construction of the corebarrels from different materials and, in the short term, by doing a round trip of the corebarrel where magnetically oriented cores are required.

b) Contamination of pore water and formation fluids

With re-circulated drilling fluids, there is a serious opportunity for contamination; great care must be taken to know the composition of the drilling fluid as well as making every attempt to obtain clean samples. It is envisaged that the sampling-while-drilling phase may have more opportunity for contamination than a later borehole monitoring phase. Instrumentation does exist for trying to minimize contamination when sampling, but more needs to be developed. The opportunity to take lateral samples after borehole completion may also assist in the collection of uncontaminated samples.

c) Contamination of rock geochemistry

This is similar to the situation above. New methodologies will be required to ensure that least contaminated samples are obtained, or that altered samples can be easily distinguished.

d) Contamination of the biosphere

The collection of biological samples may cause additional contamination because tracers are required in order to fix the samples prior to recovery. As in b) and c), careful thought will have to be given to methodology and the use of "non-contaminating" tracers introduced via the mud circulation for spot sampling. During long term monitoring the installation of a steel casing may be a problem for biological work. The material for the last liner section of the borehole should be carefully considered with the biological program in mind.

e) Artificially induced fracturing of the borehole

The formation can be fractured or invaded by excess dynamic mud pressure over formation pressure.

The borehole can be cooled while drilling; this allow tools with a lower operating temperature than that ambient in the borehole to be used. However, this induced cooling will artificially stress the rock formations (thermal cracking) and may cause collapse, as well as change the observed stress pattern in any samples recovered. There is no obvious solution to this problem, which is also one which may restrict routine coring in the deeper section of boreholes. It should also be noted that any long term monitoring tools will be required to meet the ambient pressures and temperatures of the borehole.

f) Steel-encased boreholes and borehole monitoring

The boreholes need to have a casing in order to maintain their integrity after drilling. This casing will interfere with monitoring programs and the emplacement of equipment in the formation for long-term monitoring. Very close attention will have to be paid to the phasing of any borehole monitoring program to assure that experiments do not conflict with, or preclude, any later ideas for use of the borehole.

New Technology Possibilities

a) Cross-hole Tomography

Use is already made of drill bit noise to aid lithological interpretation when drilling the borehole and for vertical seismic experiments. It is also possible that it can be used in conjunction with the pilot borehole(s) for cross-well seismic experiments.

b) Extended well possibilities

The opportunity to conduct further drilling operations by horizontal or directional drilling from the main borehole has already been mentioned. This opens the door for further seismic experiments, downhole monitoring, and the taking of core samples for lateral variation comparisons. Fluid subsampling and deep biosphere experiments may have a serious interest in obtaining samples from such lateral deviations.

c) New coring tools

All drilling and coring projects meet different geological formations. There is always a requirement to develop new sampling tools. OD21 will be no exception, and may offer opportunities for tool development within the life of a borehole in order to obtain the best information available.

d) New wireline logging tools

In similar fashion, new wireline geophysical tools can be developed for different hole diameters and temperatures, possibly making use of the enlarged hole to enable the packaging to support higher temperature work. Consideration should also be given to the development of cased hole tools for long-term monitoring experiments.

Recommendations

Drilling into the Earth's deeper layers is not an easy task, and every opportunity should therefore be taken to learn from past experiences whenever possible. A number of deep boreholes which were drilled for scientific research in crystalline rocks exist in different localities throughout the world. The drilling history, technology developments, and scientific achievements from these operations should be collated and assessed in order to give this program the best possible start. WG6 proposes such a scheme in **Appendix 1**; for consideration.

Core sampling equipment and borehole re-entry equipment which will be necessary for the program should be assessed and developed in parallel with other existing drilling programs of both science and industry. If the opportunity allowed, such collaboration would further enhance the start-up phase of this major operation.

Working Group 6 Report

All deep boreholes require as much information as possible before setting up the drilling program. The use of another drilling vessel to provide both science and geotechnical information, in addition to comprehensive site survey analysis, should be considered. **Appendix 2** suggests an "aide memoir" for searching any historical information pertinent to the drilling.

A clear management structure for the operation of the drillship is required, especially with regard to the necessity to make immediate decisions in near-emergency or emergency situations. It cannot be over-emphasized that the scientific working groups of CONCORD have set exciting and ambitious drilling targets which will pose both scientific and technical challenges. Some will cause problems which will require immediate decisions when drilling in order to maintain the integrity of the borehole and the advancement of the science. There may also be safety implications to personnel if overpressured formations are encountered. One person* must be clearly nominated as bearing the full responsibility for making decisions in regard to the total drilling operation (making hole, reaming, coring, subsampling, sidetracking, formation testing, mud engineering, including cementing and casing). That person is to have full authority, without recourse to personnel onshore, if necessary.

* It is recognized that the Master of the vessel has overall authority and can overrule even this nominated person, especially in matters of safety to personnel and the vessel.

Appendix 1

Recommendations for Knowledge Compilation on Deep Drilling in Crystalline Rocks

PURPOSE: Compile and assimilate the past knowledge in drilling in deep crystalline rocks in

- Russia (Oilfield scientific drilling in crystalline rocks: Tuyimasinskaya > 4,000 m, Mimmibaevskaya > 5000m; Continental scientific drilling program: Kola > 12,000m, Urals > 5,500m, Krivoy Rog > 5,500m, Vorotilovskaya > 4,000m, North Caucasus [geothermal] > 3,500m)
- Germany (KTB > 9,000m)
- Sweden (Gravberg 1 and 2 [Silyan] > 6,000m)
- Japan (Niigata > 6,000m)
- Iceland (Nesjavellir 370°C) - Basalt Rock but important because of the temperature

OUTCOME: Problem identification and drilling recommendations for each studied scenario.

COORDINATOR If commissioned, Dr. Maidla can coordinate the study.

SUMMARY OF SOME PROBLEMS

- Wellbore instability (by far the major problem)
- Temperature limitations
- Drilling strategy and practices:
  - * Case History
  - * Coring
  - * Cementing
  - * Mud Technology
  - * Logging Practices
  - * Drillpipe/Casing corrosion

PROCEDURE: Commission a MSc graduate student or posdoc or a consultant to build a system to model the scenarios (a graduate student is suggested based on the time frame involved). Must speak fluent English, German, and Russian and have a geomechanical and drilling background.

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DISSEMINATION Should be made public in many ways

ESTIMATED COST TOTAL COST ESTIMATION: US$ 130,000.00

M.Sc Graduate Student: US$ 90,000 total

This covers Tuition, Fees, Medical insurance, Upkeep US$30,000/ year

Estimated time to conclude: 3 years

Intermediate results: to be published: Dec/98, Dec/99, Dec/2000

Workshop with student and advisers: 2@US$20,000 each (Total $40K) This covers air trips, hotels, meals, transport, incidentals.

REFERENCES References for Concord Comments on Crystalline Rock Drilling

- *Gelfgat M.Ya., Alikin R.S., Stanko Ya.P.* Technology of ultradeep core drilling without pulling out drill pipes. In the book "Super-deep continental drilling and deep geophysical sounding", Springer-Verlag Berlin, Heidelberg, 1990.
- *Mnatsakanov A.V., Gelfgat M. YA., Alikin R.S.*: "Technology and Technique for Scientific Drilling in Crystalline Rocks: Experience and Perspectives", *paper IADC/SPE 23912 Drilling Conference,* New Orleans, February 18 - 21 (1992), 631 -643.
- *Gelfgat M. Ya.*: "Bits of History", *Oil and Gas Russia*, Vol. 3, # 1 Spring 1994, 15 - 22.
- *Yoshida, Chikao*, Deep Oil and Gas Well Drilling in Japan, VIII International Symposium on the Observation of the Continental Crust Through Drilling, Tsukuba, Japan Feb 26-28, 1996.
- KTB, Bohrtechnische Dokumentation, Umfang:800 Seiten, 591 Abbildungen und 256 Tabellen, ISSN 0939-8732, ISBN 3-928559-16-8, 1997.

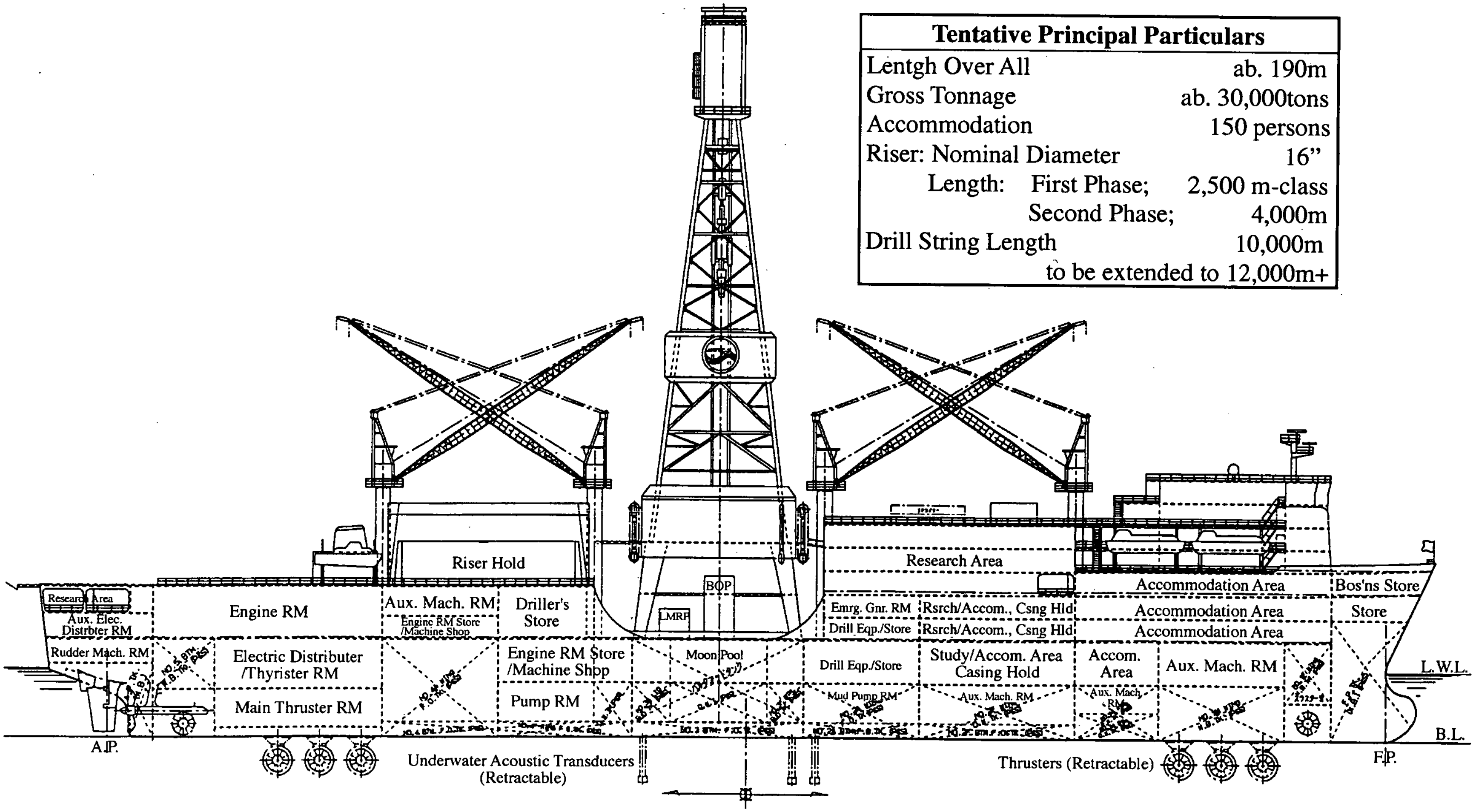
Appendix 2

Information useful for pre-drilling borehole evaluation

Geographical area - Number of sites
Water depth range
Penetration depth range
Borehole temperature estimates
Possibility of hydrocarbon occurrence and its estimated volume/origin/ setting
Degree of contamination in any subsamples which would be acceptable
Are orientated cores necessary?
Estimation of lithologies and thicknesses in borehole sequence
Is there any historical data, including industry experiences, on:
a) Borehole stability?
b) Core recovery?
c) Hydrocarbons/gas/hydrate (H_2S)?
d) Over-or Under-pressure of Formation
e) Lost circulation
f) Drilling rates

Fig. 1 Tentative General Arrangement of the Newly Proposed OD21 Drilling Vessel

Tentative Principal Particulars	
Lentgh Over All	ab. 190m
Gross Tonnage	ab. 30,000tons
Accommodation	150 persons
Riser: Nominal Diameter	16”
Length: First Phase;	2,500 m-class
Second Phase;	4,000m
Drill String Length	10,000m
	to be extended to 12,000m+



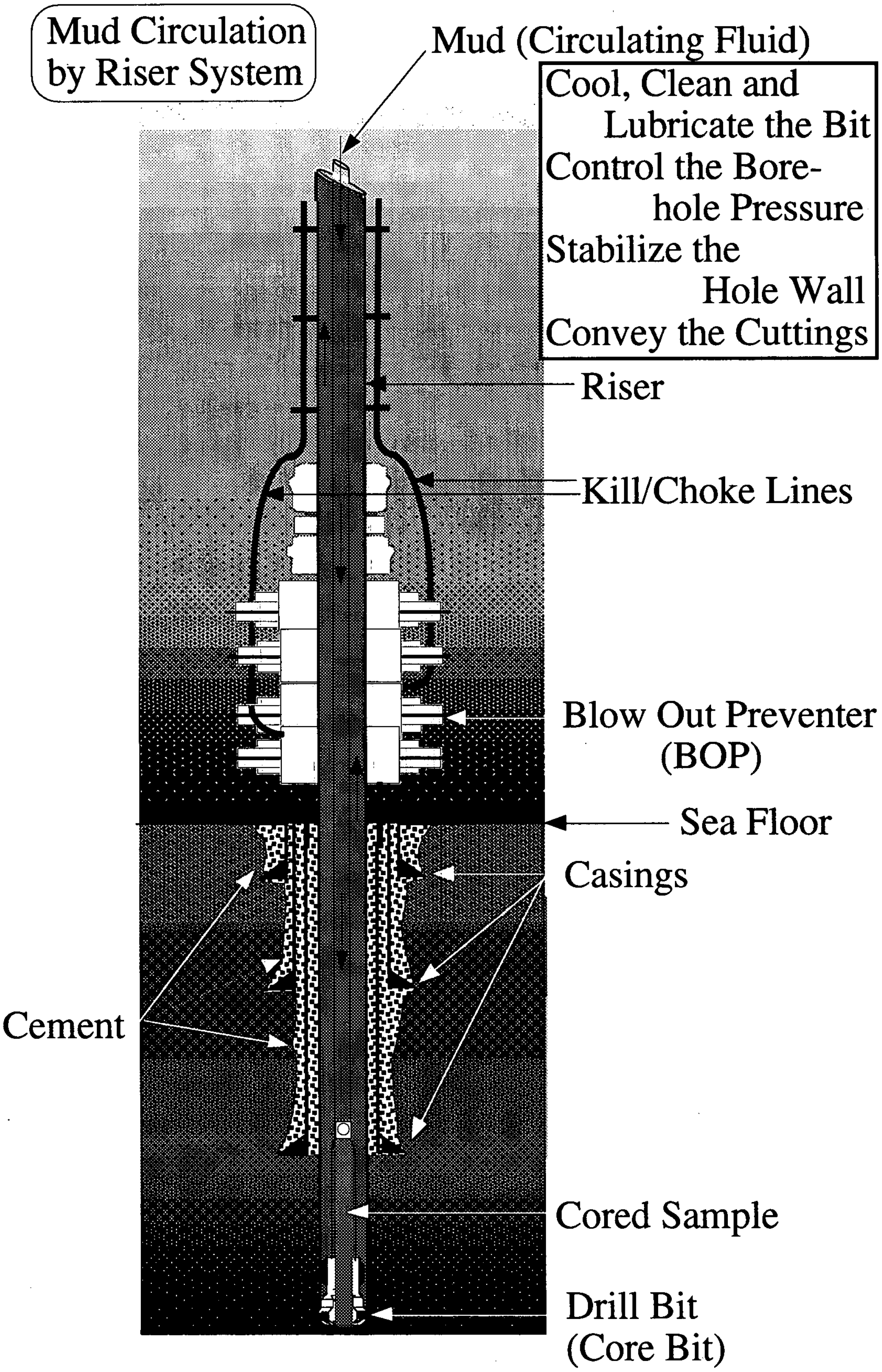


Fig. 2 General Concept and Role of Riser Drilling - Mud Circulation

Standard Casing Progam

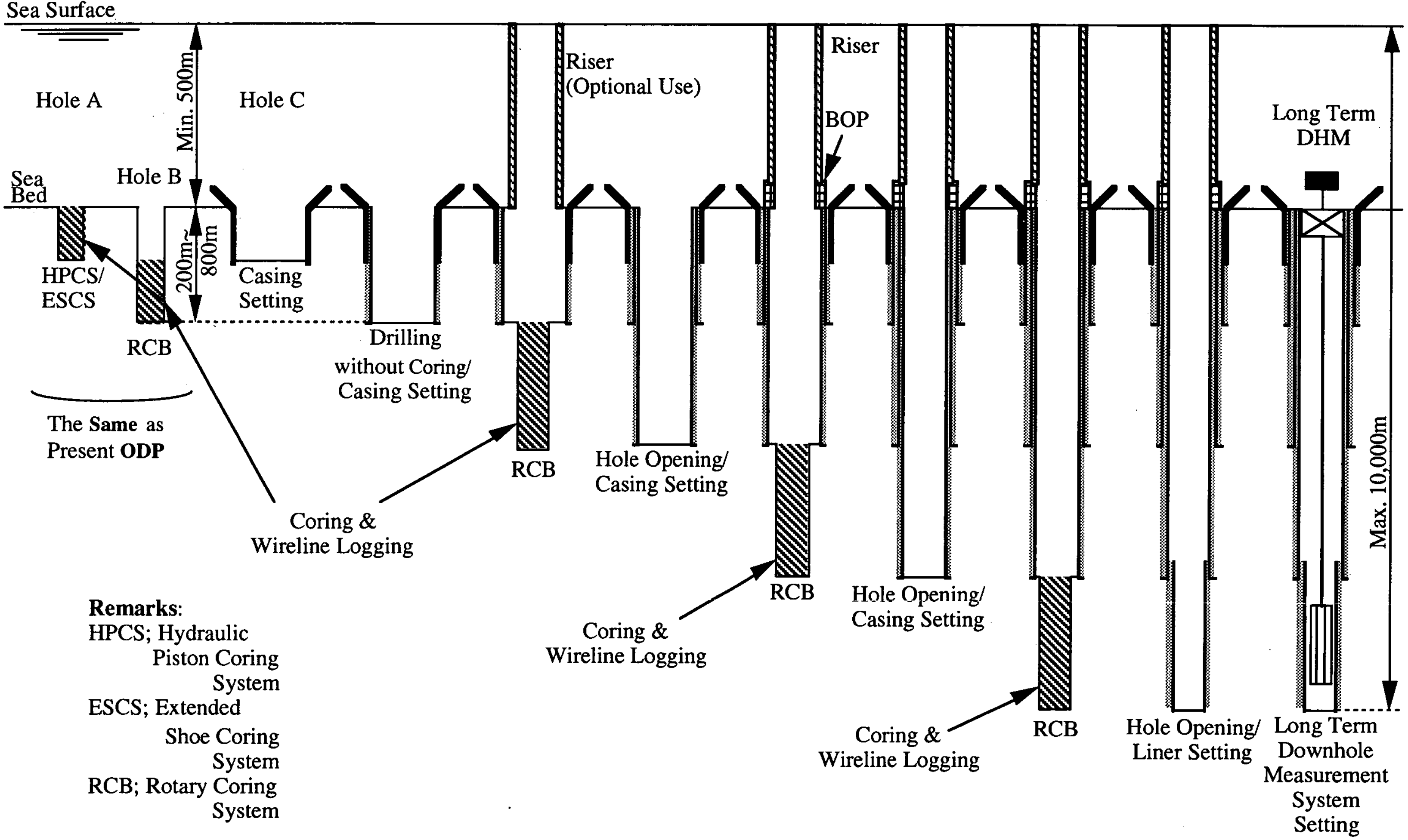


Fig. 3 Method of Drilling and Casing for a Deep Penetration Borehole

Standard Drilling Procedure for the First Stage

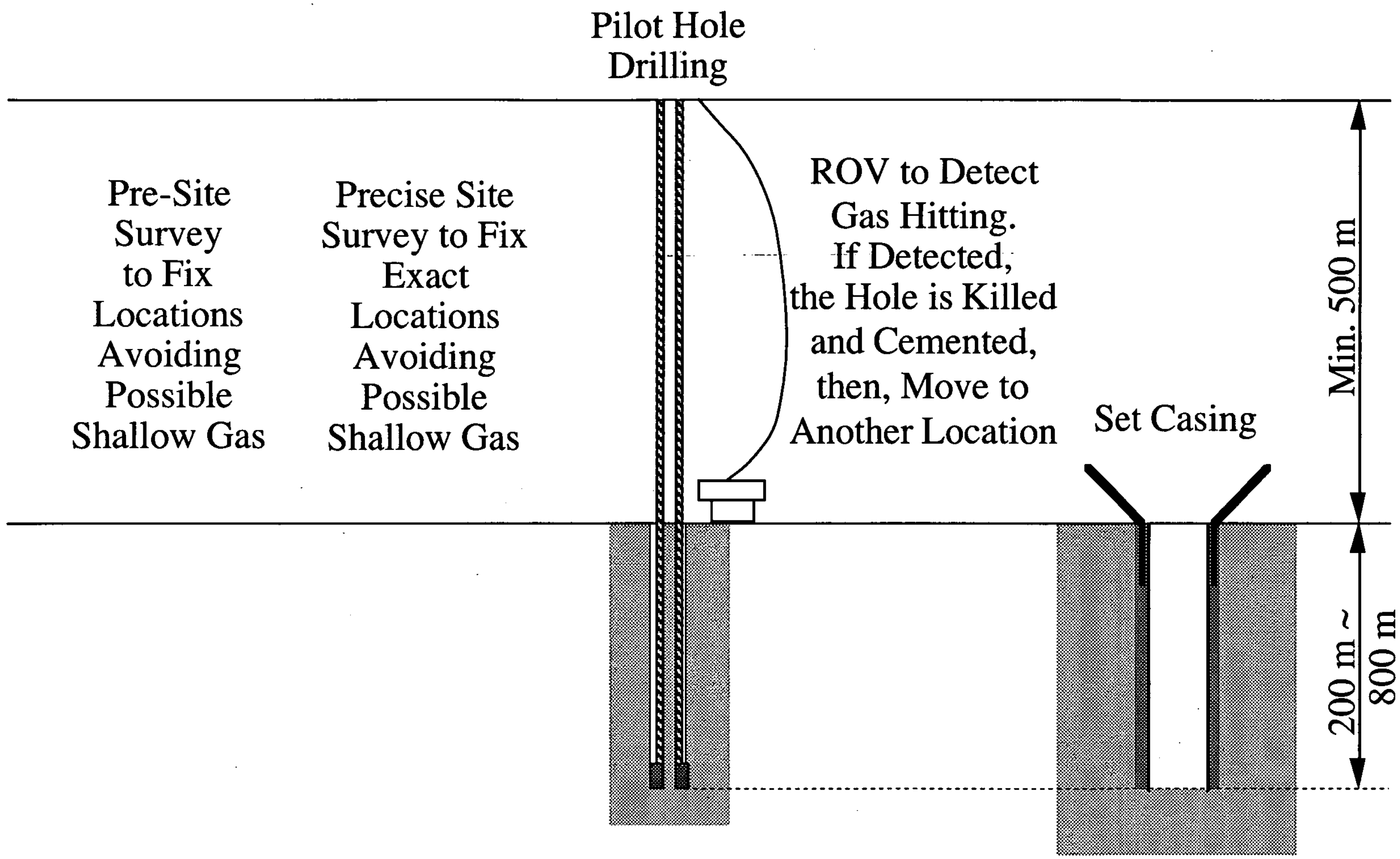
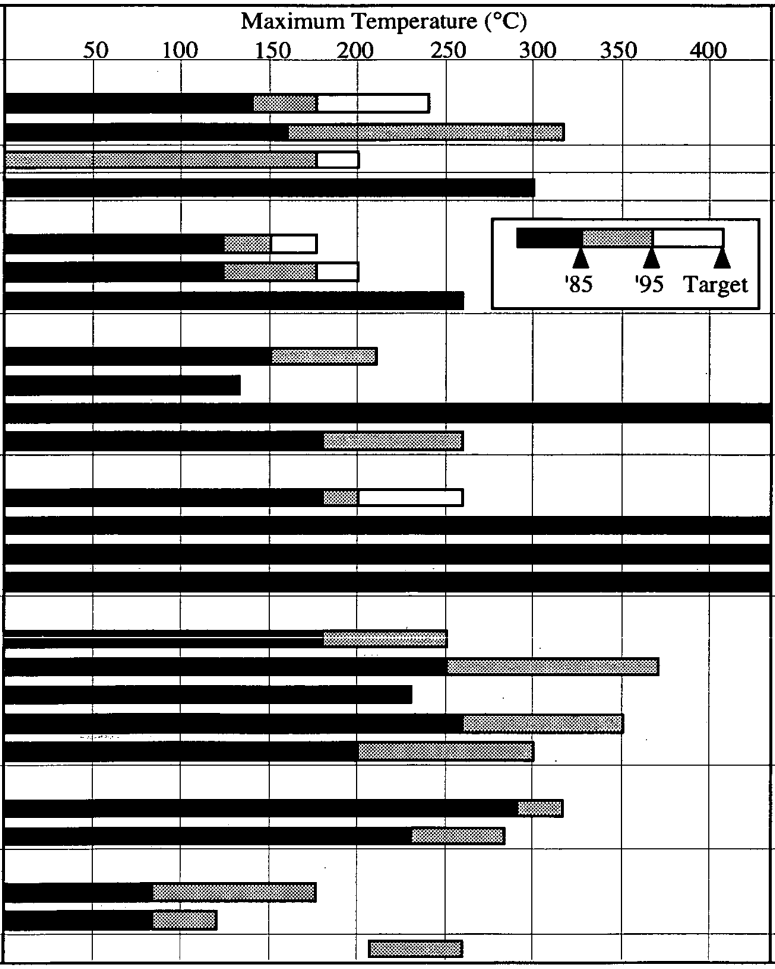


Fig. 4 A Procedure for Drilling in Possible Shallow Gas before Riser is Installed

Fig. 5 Downhole Tools and Temperature Limitation

Maximum Temperature Rating of Drilling Equipments and Materials, 1995, June, by JAPEX



Elements	1985 Max.	1995 Max.	Develop Target
Down Hole Motor			
Positive Displacement Motor	135°C	175°C	240°C
Turbine	160°C	315°C	
Vertical Drilling System	-	175°C	200°C
Core Barrel	300°C	300°C	
LWD			
Standard Type	125°C	150°C	175°C
Vertical Drilling for KTB	125°C	175°C	200°C
Heat Sealed Type	260°C	260°C	-
Cementing			
Shoe Collar	150°C	210°C	
Stage Cementer	135°C	135°C	
Cement with Silica	400°C+	400°C+	-
Cementing Additive	180°C	260°C	
Bit			
Sealed Bearing	180°C	200°C	260°C
Natural Diamond	650°C	650°C	-
PDC	750°C	750°C	-
TSP	1200°C	1200°C	-
Drilling Mud			
Water Base Mud(weighted)	180°C	250°C	
Viscosifier	250°C	370°C	
Fluid Loss Reducer	230°C	230°C	
Dispersant	260°C	350°C	
Lubricant	200°C	300°C	
Drilling Jar			
Hydraulic Type	290°C	315°C	
Mechanical Type	230°C	285°C	
Blow Out Preventer			
BOP Ram	85°C	175°C	
Casing Hanger Seal	85°C	120°C	
Liner Hanger	205°C	260°C	

Zero-Age High Temperature Drilling

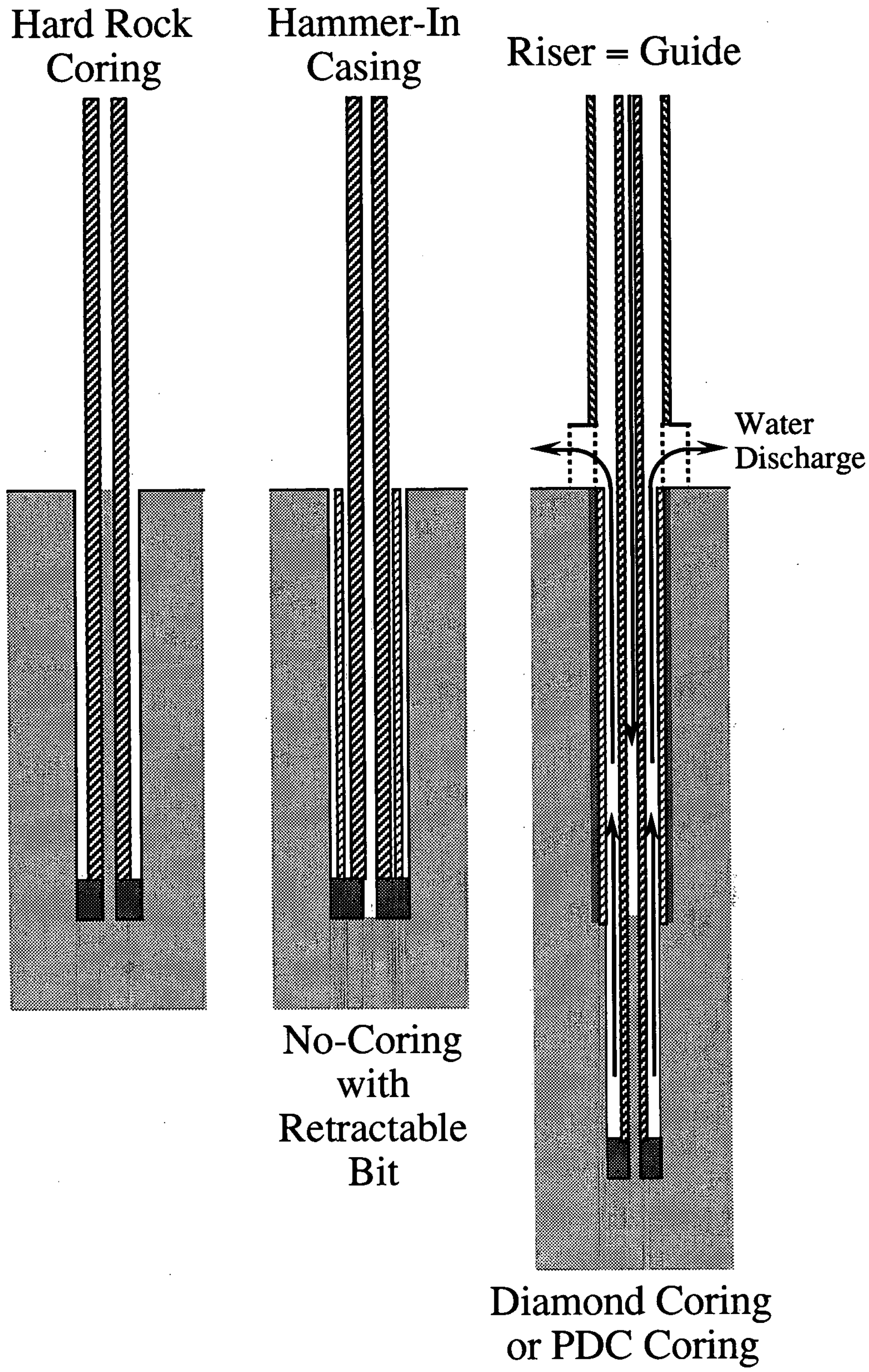


Fig. 6 Some Ways to Effect a Hard Rock Spud-In

Appendix - Agenda

A. GENERAL SCHEDULE OF THE CONCORD CONFERENCE

July 18 (Friday)	Participants in the geological field trips arrive in Japan and gather at Shin-Yokohama Prince Hotel.
July 19 (Saturday)	Geological field trips:
July 20 (Sunday)	(1) Tanzawa (leader: *Prof. M. Arima*) (2) Hakone/Izu-Oshima (leader: *Dr. K. Uto*) (3) Kobe/Awajishima (leader: *Dr. H. Itoh*)
July 21 (Monday)	Registration. Field trip participants and meeting delegates arrive at the meeting place
	Afternoon (13:00-18:00): Final Conference planning meeting (WG Chairs and Steering Committee only) Evening (18:00-19:30): Ice Breaker (all)
July 22 (Tuesday)	Main conference (The 1st day)
July 23 (Wednesday)	Main conference (The 2nd day)
July 24 (Thursday)	Main conference (The 3rd day) Adjourn of Main Conference
July 25 (Friday)	Meeting proceedings (draft) to be prepared by Task Team (WG chairs and the Steering Committee) at the Hamayu Sanso of Kurabuchi-mura in Gunma Pref.
July 26 (Saturday)	As above
July 27 (Sunday)	Completion of draft proceedings. End conference

B. DETAILED AGENDA OF CONCORD MEETING

MAIN CONFERENCE

Time: July 22 - 24, 1997
Place: National Olympics Memorial Youth Center, Tokyo, Japan

Tuesday July 22:

9:00 - 10:45; **Opening Ceremony** (Main Conference Room/Main Building 1F)

9:00 - 9:05; Welcome address by the President of JAMSTEC
Mr. T. Hirano

9:05 - 9:15; Opening remarks by CONCORD
Co-Chairs *H. C. Larsen* and *I. Kushiro*

9:15 - 9:45; Opening addresses by the Japanese Science and Technology Agency (STA): *Mr. S. Aoe*
Japanese Ministry of Education, Science, Sports and Culture (MONBUSHO): *Mr. Y. Sakitani*
US National Science Foundation (NSF): *Dr. R.W. Corell*

9:45 - 10:25; Keynote address: Solid Earth Science and Deep Sea Drilling
Prof. X. Le Pichon.

10:25 - 10:45; COFFEE BREAK

10:45 - 12:00; Plenum Session I : Background and Objectives of CONCORD
(Chaired by *H. C. Larsen*)

10:45 - 11:15; Riser drilling system. Construction and Development Plan
A. Skinner and *S. Takagawa*

11:15 - 11:40; The ODP Long Range Plan *S. Humphris*

11:40 -12:00; Introduction of Working Group Themes and Objectives of CONCORD *K. Suyehiro*

12:00 - 13:00; LUNCH

13:00 - 17:00; WG Session I: (WG participants presenting vision statements for initial discussions in the relevant WG*)

Appendix - Agenda

WG1 : No. 1/1 Meeting Room (Main Building 2F)
Chaired by *T. Loutit / H. Okada*
WG2 : No. 1/2 Meeting Room (Main Building 2F)
Chaired by *J. Erzinger / K. Tamaki*
WG3 : No.3 Meeting Room (Main Building 2F)
Chaired by *J. Mahoney / Y. Tatsumi*
WG4 : Room 901 (Study and Training Hall 9F)
Chaired by *P. Huchon /A. Taira (K. Fujioka - deputy)*
WG5 : Room 902 (Study and Training Hall 9F)
Chaired by *J. P. Foucher / K. Suyehiro*

*) WG6 members to participate in discussions within WG 1 through 5

17:00 - 19:00; DINNER

19:00 - 21: 00; WG Session II: (WG Chairs may present a preliminary summary and conclusions of the vision statements to their working group)

Wednesday July 23:

09:00 - 10:40; Plenum Session II: Presentation of initial WG progress
(Chaired by *K. Suyehiro*, at Main Conference Room)

09:05 - 09:20; WG1
09:20 - 09:35; WG2
09:35 - 09:50; WG3
09:50 - 10:05; WG4
10:05 - 10:20; WG5
10:20 - 10:40; Discussion

10:40 - 11:00; COFFEE BREAK and Transfer to Working Groups

11:00 - 12:15; WG Session III (Conference Rooms as on Tuesday)

12:15 - 13:15; LUNCH

13:15 - 17:00; WG Session IV

17:00 - 19:00; DINNER

19:00 - 21:00; Joint session of WG Chairs and Steering Committee.
Discussion on Draft Recommendation. Election of a subcommittee to draft conference recommendations. WG sessions to continue in parallel (without WG Chairs), if applicable.

Appendix - Agenda

Thursday July 24:

9:00 - 10: 45; WG Session V (Wrap-up of WG reports within each WG)

10:45 - 11:00; COFFEE BREAK and Transfer to Plenum Session

11:00 - 12:00; Plenum Session III : WG reports
(Chaired by *H. C. Larsen* and *K. Suyehiro*)

11:00 - 11:30; WG1 (NB: 6 minutes for discussion of each WG report)
11:30 - 12:00; WG2

12:00 - 13:00; LUNCH

13:00 - 13:30; WG3
13:30 - 14:00; WG4
14:00 - 14:30; WG5
14:30 - 15:00; WG6

15:00 - 15:30; COFFEE BREAK (Subcommittee on conference recommendations will meet during coffee break)

15:30 - 17:00; Plenum Session IV: Discussion and adoption of vision statement and recommendations (chaired by *H. C. Larsen* and *I. Kushiro*)

17:00 - 17:05; Closing remarks *I. Kushiro*

End of the main conference

18:00 - 20:00; RECEPTION
Reception Addresses; by *T. Hirano*, President of JAMSTEC
K. Taira, Director of ORI of the University of Tokyo
R. S. Detrick, Chair of JOIDES/EXCOM