BOREHOLE: A plan to advance post-drilling, sub-seafloor science

A Joint Oceanographic Institutions/U.S. Science Advisory Committee-sponsored workshop held at University of Miami, Rosentiel School of Marine and Atmospheric Science, Miami, Florida, on December 13-14, 1994

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Executive Summary

While ocean drilling has defined the Earth's historical record with great success, the legacy of drilling, boreholes that remain after cores have been collected, promise to provide singular observatories from which to study the nature of the Earth's interior and the active processes that control the fluxes of heat, fluid, and chemical species across the sea floor. Despite the fundamental nature of the science addressed, previous efforts by the U.S. science community to establish post-drilling, borehole-related observatories have been individual and largely uncoordinated.

A meeting, sponsored by Joint Oceanographic Institutions, Inc. (JOI) through the U.S. Science Advisory Committee (USSAC), was held 13-14 December 1994 to consider the growing need for an integrated effort to instrument and sample ocean boreholes for periods of years to decades. Although many of the objectives of post-drilling science were discussed in 1987 at a workshop on borehole re-entry techniques, this meeting began with a re-examination of the problems that can be uniquely addressed in borehole observatories. Fundamental questions include:

- What forces drive fluid flow through oceanic crust and sediments in different tectonic settings? Is that flow variable? On what time scales?
- How is flow related to the mechanical properties of the crust and sediments, local and regional stress fields, thermal flux, and phase changes of components involved in fluid migration?
- How do fluid and mechanical properties relate to earthquake occurrence at plate margins? Are there properties we can monitor in submarine boreholes to predict seismic events?
- What are the mantle and crustal properties and dynamics that create new oceanic crust at spreading centers and consume old lithosphere in subduction zones, that control the distribution of hot spots, or maintain the Earth's magnetic field?
- How is the cycle of geochemical species through oceanic lithosphere related to pore fluid advection, and what is the relationship of those elemental fluxes to global mass balances in the hydrosphere, atmosphere, and biosphere?

Although the Deep Sea Drilling Project and the Ocean Drilling Program have, together, completed nearly a thousand boreholes, only about 30 are presently suitable for post-drilling experiments and observation. Of these holes, more than half have already been used or are currently in use for experiments that include:

- Determination of seismic noise beneath the seafloor as a first step to determine the feasibility of using oceanic boreholes as elements in the Global Seismic Network
- Long-term (2-3 year) monitoring of sub-seafloor fluid pressure and temperature at active lithospheric plate margins. In situ hydrogeologic tests at the same sites define the nature and magnitude of fluid advection.
- Downhole logging for temperature, rates of fluid flow, borehole geometry and structural elements, and fluid sampling
- Long-term geochemical sampling of pore waters

Additional experiments are planned as the user community seeks to characterize transient events, define the boundary conditions that control their occurrence, and enhance resolution of both shallow and deep earth structures. As in the preliminary studies already completed, these experiments will not only monitor natural conditions, but of necessity will provide technical experience on instrument design and deployment. Plans include:

- A pilot experiment to emplace a broadband seismometer downhole in oceanic crust, and compare the record obtained there with records from an adjacent sensor buried near the sediment surface, from a seafloor seismometer, and from a terrestrial station. The program seeks to determine the relative merits of various instrument placement strategies
- A test of fault mechanisms on Juan de Fuca Ridge will induce a short-term pore pressure anomaly and monitor its effect on the pattern of natural microseismicity
- The hydrologic conductivity between two instrumented boreholes will define the hydraulic transmissivity and fluid storage capacity of shallow oceanic crust
- Seismic experiments between paired boreholes would provide high-resolution images of structural heterogeneity in the crust or sediment column
- Time-series studies utilizing seismometers, stress-strain sensors, pressure and temperature probes, and tilt meters to delineate sub-seafloor hydrologic response to seismic activity and deformation
- Establishment of a global Ocean Seismic Network after a phased program to optimize instrument deployment

Technical development to support borehole observatories has begun in numerous, independent laboratories. The report outlines some of these activities, many of which share common elements with development of seafloor instruments that is documented elsewhere. The report does note, however, that borehole installations present special problems:

- Commonly the hole must be stabilized by installation of casing and/or cementation. Because standard casing precludes some measurements, sensors may have to be mounted on the outside of the pipe or special casing materials may be required for certain experiments
- Some instruments deployed within the hole must be coupled to the surrounding rock or extend beyond drilling disturbance
- As holes often penetrate sections that are naturally isolated from each other, it will be necessary to develop the capability to partition vertical segments of the hole to prevent vertical fluid flow.
- The diameter of the casing (commonly 14-33 cm) limits the size of instruments that can be deployed downhole

Workshop participants agreed that although scientific initiatives should arise from individual investigators, there is need for an integrated support program for equipment development and testing, as well as funding for particular experiments. In a time of limited budgets, participants in the program must set priorities, share technical information, and coordinate experiments. Furthermore, any program to advance borehole observatories must be carefully coordinated with the Ocean Drilling Program, and with the international community.

The meeting participants proposed formation of BOREHOLE (BOREHole Observatories, Laboratories, and Experiments), an organization to facilitate borehole-related, sub-seafloor science. Scientific and technical elements of a BOREHOLE program should include:

- fundamental scientific research at borehole-related installations
- feasibility studies to evaluate techniques and instruments
- new instrumentation development
- establishment of reference sites for instrument testing and calibration

The BOREHOLE program would provide coordination, management, and planning for a strategic initiative to advance understanding of sub-seafloor processes. To this end, the program should:

- develop science and technical priorities among participants
- conduct workshops to discuss scientific objectives and strategies, to aid development of instrumentation, and to plan long-term experiments
- provide technical information to the user community
- with JOIDES and USSAC, formulate US positions on observatories and experiments
- coordinate instrumentation and facility development with the ODP Engineering Division and with the continental drilling community;
- develop funding sources for observatories and post-drilling experiments.

To implement these objectives, the report proposes the following BOREHOLE structure:

- a Steering Committee of 5-8 members, approved by the Joint Oceanographic Institutions (JOI) Board of Governors.
- a Program Director to provide management services for the Steering Committee, and to oversee operation of the program.

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2. Agenda

Tuesday, December 13

Introduction

+ Welcome and introduction - Keir Becker
+ Rationale for a workshop on post-drilling science- Bobb Carson

Summary of scientific objectives of post-drilling investigations

+ Borehole logging instrumentation and techniques - David Goldberg
+ Deep earth structure, lithospheric flow, and nature of plate movement - Rhett Butler
+ Physical properties of upper crust and sediments - Ralph Stephen
+ Chemistry of formation waters and solid phases - Joris Gieskes

Working groups:
1. Earth structure and physical properties - Leaders: Mike Purdy and Fred Spiess
2. Heat, fluid, and chemical fluxes - Leaders: Earl Davis and Robert Zierenberg
    + Discussion to define scientific goals, hypotheses, objectives that require post-drilling investigation
    + Summary of scientific goals by working group leaders

Technical base for post-drilling science

Working groups:
    + Discussion to consider the technical and logistic requirements to accomplish the science objectives and need for borehole or seafloor laboratories, instrument development, ship support, and sampling protocols.

- Summary of technical requirements by working group leaders

Wednesday, December 14

- Re-entry site issues: Existing inventory; siting new holes; engineering considerations - Keir Becker

Structural needs to advance post-drilling science

+ Summary of programmatic and funding issues by working group leaders
+ General discussion of programmatic changes and funding needs required to effect the scientific and technical objectives.

Preparation of recommendations for JOI/USSAC workshop report

3. Introduction

In December 1994, members of the U.S. geoscience community met in Miami, Florida under JOI-USSAC sponsorship, to consider the growing need for an integrated effort to instrument and sample ocean boreholes over extended periods - that is, to establish post-drilling, borehole-related observatories. Recent years have witnessed several independent approaches to long-term borehole experiments, with specific objectives ranging from studying seafloor hydrogeology to determining deep Earth structure. These objectives are among the highest priorities of the Ocean Drilling Program (ODP), as stated in several ODP planning documents (e.g., the COSOD II Report, the ODP Long-Range Plan). For reasons detailed below, the most effective way to address some of these key ODP objectives is through long-term post-drilling experiments. However, ODP itself is neither mandated nor specifically funded to utilize its holes in this way. The consensus of the meeting was that there are significant scientific, logistic, and fiscal advantages to organizing a national effort to utilize ODP holes for long-term experiments. This report presents these advantages, in support of a call to formally establish a program of post- drilling BOREHole Observatories, Laboratories, and Experiments (BOREHOLE).

The 1994 BOREHOLE meeting traces many of its roots back to the 1987 USSAC-sponsored meeting on Science Opportunities Created by Wireline Re-entry of Deep Sea Boreholes (Langseth and Spiess, 1987), which detailed scientific objectives made possible by borehole re-entry and recommended development of re-entry capabilities. That meeting foresaw the demand for post-drilling seismic, resistivity, and electromagnetic experiments to delineate crustal structure, for hydrogeologic determinations of pore pressure, permeability, and water chemistry in holes that had equilibrated after drilling, and for emplacement of long-term observatories to monitor tectonic motion, heat flow, and earthquake activity. The 1987 workshop focused on crustal studies, but other geologic settings, notably sedimentary sections on convergent and passive continental margins, have subsequently become important foci for extended, post-drilling science. In these settings, the flux and diagenesis of hydrocarbon-bearing fluids, the nature of gas hydrates, and the effects of gas/fluid phases on slope stability are topics of active inquiry that will require experimentation in established boreholes for solution. Whether the interest focuses on the crust or the sediment column, however, it is becoming increasingly apparent that study of active processes at and below the seafloor requires observation, experimentation, and sampling in holes that have recovered from drilling-induced disturbance, over time periods that range from months to years.

Following the 1987 workshop, several independent, and largely uncoordinated efforts to emplace instruments in boreholes were brought to completion. A Control Vehicle system was developed at Scripps that allows re-entry in ODP boreholes from surface vessels, while IFREMER in France produced a comparable submersible-based system (NADIA). A joint ODP-U.S. university-Canadian Geologic Survey effort developed instrumented borehole seals (CORKs), capable of hydraulically isolating boreholes from the ocean bottom water, that provide multi-year logs of downhole temperature and pressure. Other individual and collective efforts are underway. A 3-component, broad-band seismometer for downhole deployment is currently under construction for the Ocean Seismic Network (OSN), and independent investigators are developing post-drilling fluid samplers for geochemical analyses.

Although advances have clearly been made in developing post-drilling instrumentation, and early experiments have yielded important results (Gable and Party, 1992; Montagner et al., 1994a; Montagner and Lancelot, 1995; Stephen et al., 1994; Davis and Becker, 1994; Davis et al., 1995; Screaton et al., 1995), there has been no coherent national effort to facilitate establishment and maintenance of seafloor observatories at boreholes. The report below summarizes scientific objectives that require post-drilling observation, examples of past and proposed experiments to meet those objectives, the technology required to carry out these programs, and details recommendations for an administrative structure to enhance the efficiency of US efforts in this rapidly evolving scientific arena.

4. Scientific Objectives of Post-Drilling Science

4.0 Introduction

Although DSDP/ODP coring and logging have addressed the Earth's historical record with great success, the study of active processes at and below the seafloor requires experimentation and sampling in holes that have recovered from drilling-induced disturbance. Fundamental scientific questions about deep earth structure, about mechanisms of crustal formation and evolution, and about modern processes of sediment accumulation can be uniquely addressed by seafloor experiments.

Recent recognition that active fluid convection plays a critical role in many of these problems dictates that we determine, in-situ, the relationships between fluid pressure, permeability and porosity, mechanical properties of the crust and sediments, regional and local stress fields, and phase changes of components involved in fluid migration. We also need to understand the importance of transient events and of the balance between diffuse flow and flow focused along structural pathways. We must determine the flux of geochemical species that are controlled by the physical flow of pore waters, and relate that flux to global mass balances in the Earth's hydrosphere and atmosphere. Equally important is examination of the driving mechanisms on several scales: local and regional heat sources, formation-scale sediment compaction patterns, organic and inorganic evolution of hydrocarbons, and the relation of these processes to structure, stress accumulation, seismic events, and dynamic evolution of plate-margin tectonic settings.

These larger questions can be adequately answered only in the context of improved understanding of dynamic processes associated with lithospheric plate evolution and destruction. Understanding the most fundamental processes in earth sciences today requires knowledge of the deep structure of the earth, from the inner core to the upper mantle. The recording of teleseismic earthquakes by permanent observatories distributed over the continents and on some islands has provided the seismological data most able to constrain the properties of deep earth materials and the characteristics of the active processes that, for example, control the distribution of hot-spots or maintain the earth's magnetic field. However, traditionally these studies have been hampered by the uneven distribution of measurements available from the existing land-based network of seismic and geomagnetic observatories. Hence, a fundamental objective of a borehole observatory program must be improved resolution of deep earth structure through deployment of sub-seafloor seismic and geomagnetic stations.

4.1 Fluid Flow in Crust and Sediments

The circulation of fluids through the porous oceanic crust and sediments is of vital importance to the Earth's chemical and thermal balances. For example, about 25% of the heat loss from the Earth occurs by hydrothermal circulation of pore fluids and seawater through oceanic crust (e.g., Sclater et al., 1980). Integrated over space and geologic time, crustal hydrothermal circulation has a profound effect on the chemical and physical state of the crust, as well as the chemistry of the oceans. Although fluid flow in many oceanic sediments is insignificant, near lithospheric plate boundaries - at subduction zones and strike-slip margins and on sedimented ridge flanks - pore fluids are known to advect rapidly. Significant advective flow is also inferred on passive margins where terrestrially-sourced aquifers discharge as submarine springs. In these locations, chemical fluxes are controlled by the rate of fluid flow, and involve inorganic as well as carbon and sulfur compounds that may be important to seawater composition and, ultimately, climate change.

Such fluid flow can probably be divided into three categories, depending on the driving forces: thermally-driven hydrothermal circulation in young oceanic crust, tectonically-driven dewatering in accretionary settings, and gravitationally-driven flow on continental margins. Whatever the ultimate cause, flow rates and patterns are controlled by the differential pressure gradient and permeability along the flow path. Despite the known importance of fluid flow in oceanic crust and sediments, it remains poorly understood in detail, largely because it is an active process that requires in-situ study - which is simply not possible with any conventional oceanographic techniques. Standard hydrogeologic tests must be conducted in situ, because they involve perturbation of the natural pore water system and observation of its recovery.

Understanding all aspects of fluid circulation in oceanic crust and sediments has long been recognized as a primary goal of the ODP and was specifically high-lighted in the COSOD II Report (pp. 67-86). ODP drilling is one of our most powerful tools for assessing the physical and chemical nature of the widespread fluid circulation through oceanic crust and sediments, by providing in situ "windows" into the fluid flow systems. Such "windows" will ideally provide the opportunity to sample the circulating fluids, to measure the properties that control the circulation - permeability, porosity, and pressure gradients - and to monitor the active processes over long-term.

However, holes that are left open, as is standard ODP practice in the deep ocean, do not represent truly in-situ conditions, because of the disturbance that results from drilling and the hydrologic "contamination" allowed by open hydraulic communication with the ocean bottom water. Unfortunately, the magnitude of such disturbances is often greatest where natural hydrogeological processes are most active and where scientific interest is therefore most keen, e.g., in young oceanic crust and at accretionary complexes. For example, there are many documented cases of downhole flow in DSDP/ODP holes that penetrate young oceanic crust (e.g., Erickson, 1975; Hyndman et al., 1976; Becker et al., 1983, 1984, 1989). As long as there is sufficient formation permeability, such downhole flow may be induced either by the pressure differential between "cold hydrostatic" drilling fluids and less dense "hot hydrostatic" formation fluids, or by possible dynamic formation underpressures (e.g., Anderson and Zoback, 1982; Davis et al., 1992).

Such flow in open holes certainly affects our attempts to assess the hydrologic properties of the formation and sample formation fluids, and may also actually disrupt the natural hydrogeological processes we are trying to understand. To fully realize the potential of ODP holes for studying fluid circulation in situ requires control of such flow in ODP holes, so that truly in-situ conditions can be monitored after drilling disturbances have dissipated. This in fact is precisely the objective of the CORK observatory described in detail below.

Full understanding of sub-surface fluid regimes requires numerical modeling. At present, however, the boundary conditions to constrain such models in fluid-active submarine environments are so poorly known that solutions are often not unique. Seafloor and borehole observatories are necessary to monitor pressure over time periods from hours to decades, and to provide sites for active hydrogeologic tests to define in situ permeability and storativity. These data, combined with complementary structural and geophysical results, are necessary to formulate realistic three-dimensional models of sub-surface fluid flow.

4.2 Geochemical Fluxes

To paraphrase from the COSOD II Report, fluid circulation in rock and sediments beneath the seafloor is a first-order global process that directly affects two major chemical cycles: the cycle of elements through the atmosphere, hydrosphere and biosphere, and the cycle of elements through the sediment, crust and uppermost mantle of the oceanic lithosphere. Quantifying these fluxes, in particular the fluxes between the major chemical constituents of sea water seawater (Na, Cl, Ca, Mg, Sr, K, SO_4, Li, B) and the underlying sediments and oceanic lithosphere, is essential to understanding global geochemical cycles. Although river fluxes of most constituents is reasonably constrained (Martin and Meybeck, 1979; Meybeck, 1979), exchange between the ocean, oceanic sediments, and oceanic crustal basalts is poorly understood. The fluxes between the oceans and underlying sediments/lithosphere generally fall into 3 quite different categories: fluxes associated with hydrothermal circulation, fluxes in subduction fluid expulsion processes, and gravitationally-driven fluxes in fluid circulation systems in continental margins and shallow platforms. Estimates of the magnitude of hydrothermal geochemical exchanges involving ridge crest axial systems differ widely. The large estimates of Edmond (1979) for the chemical fluxes associated with ridge crest hot springs may be overly optimistic (Thompson, 1983). And although hydrothermal circulation through ridge flanks is clearly important to cooling of the earth, its role in global geochemical cycles is highly uncertain (Mottl and Wheat, 1994). Geochemical budgets at convergent and passive continental margins are also poorly constrained. For example, carbon on margins is transported with advecting pore water as both fluid and gaseous hydrocarbons, expelled to the water column in unknown quantities, and sequestered within the sediment column as microbially-mediated carbonate deposits and as gas hydrates. We are probably aware of the principle species involved in the carbon budget, but fluid flow, speciation between gas, solid, and fluid phases, and the kinetics of major reactions are inadequately understood.

The COSOD II Report recommends a "hydrodynamic approach" to understanding these fluxes, such that fluxes estimated from samples and measurements in a few representative boreholes may be extrapolated to global scale. Understanding the geochemical fluxes in these representative holes requires careful study of the time-integrated geochemical effects of fluid flow on the core, determining the physical controls on fluid flow as described in the section above, and adequately sampling the circulating fluids. The last probably requires a borehole, except perhaps in the upper sediments from which pore fluids can be sampled or squeezed. However, the process of drilling the borehole seriously contaminates the fluids in the vicinity of the hole for some time after drilling. Thus, utilizing a borehole for fluid sampling almost certainly requires post-drilling operations, whether short-term revisits for borehole fluid sampling or long-term monitoring/sampling.

4.3 In Situ Physical Properties of Oceanic Crust and Sediments

In situ properties of the oceanic crust and overlying sediment column can only be adequately characterized through measurements in seafloor boreholes. Such data are the key to understanding far more voluminous records of remote geophysical observations collected during decades of marine geological and geophysical expeditions. Seismic, gravity, magnetic, and heat flow surveys return simple expressions of complex sub-seafloor processes and structures, that must be "ground-truthed" at boreholes under in situ conditions.

Post-drilling experiments, both short and long term, allow for collection of data not available from shipboard measurements due to time constraints, hole equilibration criteria, or physical constraints (e.g., ship heave). For instance, we have only a limited understanding of the effect of the physical drilling process on measurements made shortly after coring. Repeat visits to Hole 504B have illustrated the lengthy course of re-equilibration of the thermal gradient once drilling has ceased. How this process operates in a borehole that has been sealed or vertically segmented has never been documented.

A fundamental unknown is the in situ pore pressure. Drilling forces water into formations preferentially in porous layers or zones of weakness, sometimes even hydraulically fracturing the material immediately adjacent to the borehole. This hydrofracturing is largely uncontrolled during drilling, yet will yield valuable new data on the pressure dependence of natural fracture permeability and, perhaps, the stress anisotropy, if it is performed as a controlled, post-drilling experiment. Transients in pore pressure are also important indicators of physical processes. Davis et al. (1995) have recorded tidally-induced pressure fluctuations in a sealed borehole (ODP Site 892) on the Cascadia margin. The amplitude of these pressure pulses transmitted through sediment and crustal pore structures, and their attenuation with depth, describe permeability around the borehole. Non-cyclical events, such as storm surges, may play a role in overall fluid circulation in locations such as passive margins not dominated by other active processes. Furthermore, we know nothing of the relationship between pore pressures and seismicity. Long-term monitoring of pore pressures in fault zones will help to uncover the extent to which elevated pore pressures influence the timing and location of earthquake and landslide events (or are influenced by those events).

Borehole observatories will allow long-term monitoring of the effects of phase changes on properties below the seafloor. In hydrothermal systems or areas of cold seeps, precipitation of minerals in pore spaces should produce measurable differences in formation velocity, permeability, and electrical resistivity over time spans realistic for borehole observatories. Measurable changes in these parameters may also occur upon re-establishment of gas hydrate layers disturbed by drilling. Indeed, such experiments would provide the first determinations of in situ rates of hydrate formation, and proportion of the pore spaces that they occupy.

Gravimeter surveys of oceanic boreholes are needed to describe the detailed density distribution around boreholes, which is fundamental to determining the nature of the porosity, diagenetic deposition, sediment compaction history, and large-scale fracturing. These surveys cannot be accomplished from the drillship because of the disturbing effects of ship heave and vibration, as well as the fact that available gravimeters are not narrow enough to fit through the ODP bottom hole assembly.

4.4 Deep Earth Structure and Processes

It is a high priority to establish permanent broad-band seismic observatories on the ocean floor (Purdy and Dziewonski, 1988) and a number of research programs are actively working towards this goal not only in the US but also in France and Japan.The name of this program is OSN (Ocean Seismic Network). It is likely that high quality broad band seismic data can be obtained from the ocean floor only by using sensors that are emplaced within drill holes that penetrate the volcanic ocean crust. Therefore it is clear that the OSN and BOREHOLE programs will share many common goals. The specific objectives of OSN have been presented in recent US national (Purdy and al., 1995) and international reports (Montagner and Lancelot, 1995) and therefore only a brief overview will be presented here.

The lateral resolution of current tomographic models of the earth's mantle is approaching ~1000-1500km. As this resolution improves, it is feasible to study more detailed features of the models. Examples of key issues that would benefit greatly from data provided by oceanic broadband borehole seismic observatories are :

- **Upper mantle anisotropy**: for example, does the upper mantle anisotropy observed today reflect the current flow pattern in the mantle or is it 'left-over' from the process of formation of the lithosphere?

- **Structure at the Core-Mantle Boundary (CMB)**: knowledge of the chemical/thermal processes occurring at the base of the mantle require improved constraints on the suggested very large (several %) lateral variations in shear wave velocity in this region, as well as more reliable determinations of anisotropy.

- **The Characteristics of the Lateral Heterogeneity of the Mantle:** the convective regime in the mantle can be constrained because the configuration of the convective cells will determine the spectral characteristics of thermal heterogeneity at different depths within the mantle. Existing tomographic models based on presently available data sets disagree on some important features.

- **Mantle Convection:** it remains uncertain as to whether the primary circulation in the mantle involves the entire mantle, or whether the upper and lower mantle convect separately. Do lithospheric slabs penetrate into the lower mantle? What is the three-dimensional geometry of hot upwellings?

- **Depth Extent of Mid-Ocean Ridges:** What are the important differences between slow and fast-spreading ridges? Is the flow beneath ridges directly related to the main upwellings of global mantle circulation, or are they the results of flow deflected from under thick lithospheric plates?

5. Examples of Post-Drilling Downhole Experiments

5.0 Introduction

Borehole-related observatories can delineate dynamic earth processes over periods of seconds to decades. Equipped with a variety of sensors, they record subsurface data and provide real-world boundary conditions for numerical models that characterize transient elements of deep earth structure, of oceanic crust, and of marine sediments. Some of the data reflect continuous changes (e.g., pore pressure fluctuations in tectonically active regions) while others record discrete phenomena (e.g., natural seismicity). In contrast to passive observation, some sub-seafloor characteristics (e.g., permeability) can only be determined by active experimentation. In these analyses, natural conditions are often perturbed in a controlled manner and the response to this intervention is monitored.

In this section, evidence is presented of the health of post-drilling borehole science by describing examples of research in three categories: programs that have been completed recently, programs that have been funded and will be carried out in the immediate future, and existing plans for future major programs. This is not an all-inclusive list; the examples are intended to convey only the extent and diversity of the research interest and to establish the existence of an active community dedicated to the successful achievement of the objectives described in this report.

5.1 Examples of Recent Accomplishments

• 5.1.A: Very Low Frequency Ambient Noise Beneath the Seafloor

In high quality seismic stations on land, seismometers are installed in underground vaults and boreholes in order to reduce the background ambient noise levels and to obtain good coupling to true earth motion. The sources of seismic noise, such as surf on beaches or the wind through the trees, and the propagation of noise, as interface waves, combine to make the surface a relatively noisy environment. Also the surface is often the site of poorly consolidated material such as mud and gravel which make clamping the seismometer difficult or impossible. A similar situation has been postulated for the seafloor.

A number of seismic experiments in various frequency bands have been carried out or are being planned in order to quantitatively test the improvements that borehole seismic installations can make on the seafloor. One example was the Low Frequency Acoustic Seismic Experiment (LFASE) which was specifically designed to study the ambient noise field in the upper 100m of sediments in the frequency band from 2.0-50Hz. The LFASE experiment was carried out in the Blake-Bahama Basin off the coast of Florida in August 1989. More recently, the Seafloor Borehole Array Seismic System (SEABASS) was built to install a four-node array of three-component seismic sensors and to autonomously record the data for a period up to a month (Stephen et al., 1994). SEABASS was deployed using the wireline re-entry system (Spiess et al., 1992).

Ambient noise data from LFASE averaged over a one week interval are summarized in Figure 5.1-1 (Bradley, 1994). The acceleration spectra are compared at three depths in the seafloor (10, 70 and 100m) against an Ocean Bottom Seismometer (OBS) on the seafloor. The spectra show that ambient noise is quieter below the seafloor at frequencies between 0.5 and 20Hz for both vertical and horizontal acceleration. Horizontal acceleration noise levels in the range 0.3-1.5Hz are considerably less at 70m and 100m depth compared to the seafloor or shallowly buried (10m) levels. Above 1.5Hz most of the improvement in noise levels is obtained in the upper 10m.

INSERT FIG. 5.1-1 HERE

Figure 5.1-1: Depth dependence of VLF ambient noise at Site 534 in the Blake-Bahama Basin with a water depth of about 5,000 m and a sediment thickness of about 1,000m. At the microseism peak at 0.3Hz the noise levels for both horizontal and vertical channels are independent of depth. Above 0.3Hz the levels on the borehole sensors (SEABASS) are 10-15dB lower than on the seafloor (OBS). The greatest decrease in noise levels occurs on the horizontal channels. From Bradley (1994).

• 5.1.B: Hydraulically Sealed Boreholes (CORKs)

At Hole 892B on the Oregon Margin, an instrumented borehole seal (Circulation Obviation Retrofit Kit, CORK; Davis et al., 1992) that hydraulically isolates the hole recorded pressure and downhole temperatures for two years after deployment in 1992. In addition, active hydrogeologic tests were conducted at the CORK with the submersible *Alvin* 10 months after shut-in. The combined results of these studies have proved essential to understanding both the hydrogeology and the origin of gas hydrates at the site (Davis et al., 1995; Carson and Westbrook, 1995).

The 146 m-deep hole at Site 892 penetrates a hydrologically active thrust fault at about 100 mbsf, as well as a bottom-simulating reflector (BSR) at 72 mbsf, about 8 m shallower than its regional depth. The anomalous BSR position reflects the thermal effects of fluid flow in the fault zone. Temperatures in the sealed hole define a generally uniform gradient of about 0.068 ^{o}C/m, which gives a temperature at the depth of the regional BSR identical to that on the seawater-methane-hydrate phase boundary at the equivalent pressure. The CORK temperatures also define a distinct thermal anomaly at the depth of the fault zone, suggesting a transient up-dip fluid flow event at a rate of about 6×10^{-5} m^3/s, nearly two orders of magnitude greater than an average steady-state rate inferred from the 8-m shoaling of the BSR within the fault zone.

The section penetrated by the hole was expected to be overpressured and borehole pressures at the time of drilling were indeed superhydrostatic (Screaton et al., 1995). However, the long-term CORK record (Fig. 5.1-2) shows in-hole pressure decayed to a relatively stable value of only 13 kPa above hydrostatic within 6 months of drilling. The initial superhydrostatic pressures may have been caused by charging of the formation during drilling, although the combination of CORK data and active formation testing by Screaton et al. (1995) using both a packer and pump tests at the CORK itself suggests a more likely alternative: that high pressures were present in the fault zone prior to drilling, but were drained after the fault was penetrated, probably to some portion of the formation within the section spanned by the open hole, where lower fluid pressure may occur. Closure of fractures upon pressure decay resulted in a permeability reduction of 2-4 orders of magnitude, and established fault zone flow control by pressure-dependent secondary porosity.

INSERT FIG. 5.1-2 HERE

Figure 5.1-2 Pressure versus time in Hole 892B following installation of an ODP CORK. Seafloor pressure is determined from in-hole absolute pressure measurements recorded hourly by the CORK data logger and differential pressure (hole versus seafloor) data collected by submersible 10 months after shut-in. From Davis et al. (1995).

Finally, the attenuation and phase lag of the tidal signal recorded in the sealed hole (Fig. 5.1-2) suggest the presence of about 2% free gas in the pore volume of the sediments, confirming the inference that free gas is present in the formation below the BSR.

• 5.1.C: Logging by Wireline Re-entry

One of the major thrusts of the 1987 wireline reentry workshop was to present the case for post-drilling logging by wireline reentry of selected holes. Several expeditions have shown that logging by wireline reentry is feasible, using either the Scripps' MPL Control Vehicle or the French submersible-deployed shuttle NADIA. In most of these deployments, the logging measurements were simple temperature and/or caliper logs taken prior to installation of seismometers. In one case, however, the entire focus of the expedition was logging measurements and fluid sampling by wireline reentry. This was the French-American DIANAUT expedition in 1989, in which 3 Atlantic holes (DSDP Holes 333A, 395A, and 534A) were reentered for a logging program oriented towards understanding hydrogeology (Gable et al., 1992, and other papers in the same special section of Geophysical Research Letters).

The DIANAUT logging program included temperature logs, fluid sampling, flowmeter logs, and borehole televiewer logs. The first two measurements (temperature and fluid sampling) require equilibration times from the drilling process on the order of weeks to months for valid results and are thus effectively made only in post-drilling operations. The second pair of measurements (flowmeter and televiewer logs) represent tools that are very heave-sensitive, for which wireline reentry provides a more stable platform and resulting higher data quality. Other kinds of tools, not run during the DIANAUT program, that require wireline reentry capability include those too large to be run from the drillship, such as gravimeters.

5.2 Examples of Programs under Active Development

• 5.2.A: Plans for Pilot Experiments at the OSN-1 Drill Site

Several important technical and physical questions must be answered before high quality, broad-band seismic data are routinely collected from the ocean floor. The most crucial issues are related to the sensor - its control, leveling and emplacement on or beneath the ocean floor in order to minimize background noise and insure high fidelity recording of ground motion (especially horizontal movements). The construction of permanent ocean floor seismic observatories should not begin until an improved understanding has been gained of the factors that determine the optimum mode of sensor emplacement. Experiments by Japanese (Suyehiro et al., 1992) and French (Montagner et al., 1994a,b) colleagues have already proved that the fundamental goal of recording useful broad band data on the deep-ocean floor is realizable, but have left unresolved the key issue of whether it is essential to install sensors down boreholes into basaltic basement. In recognition of this problem, a meeting was held in 1991 to define the components of experiments that would serve to answer some of these questions, and provide the community with the data necessary to make sound decisions about the optimal approaches to broad-band recording on the ocean floor. The report from this meeting (Forsyth et al., 1991) calls for quantitative comparisons to be made between 3-month long broadband recordings collected in four contrasting environments: within a borehole drilled into basaltic oceanic basement, a package buried beneath the seafloor in the surficial sediments; a package resting on the seafloor; and a nearby conventional GSN island station. The borehole (ODP Site 843B, also designated OSN-1) required by this plan was drilled at the location shown in Figure 5.2-1 in 1991 (Dziewonski et al., 1992). During the intervening years, funding has been secured from the National Science Foundation to support both the design and construction of the necessary instrumentation, and cruises required to emplace and recover the instruments and retrieve the data. These efforts involve a number of investigators from Scripps Institution of Oceanography, the University of Miami, and Woods Hole Oceanographic Institution.

INSERT FIG. 5.2-1 HERE

Fig. 5.2-1 Location of the OSN-1 drill hole (ODP Site 843B), 225 km southwest of Oahu. Water depth is 4407 m, sediment thickness is 244 m, and the hole penetrates ~ 70 m into basement. From Dziewonski et al. (1992).

Plans are in place for a cruise in early 1997 to deploy the instrumentation for the pilot experiments at ODP Site 843B (OSN-1). The primary measurements that will be carried out are a three-month-long continuous recording of broad-band data from co-located downhole, seafloor and surficially buried sensors and the comparison of these results with those from a nearby GSN island station (in this case the Kipapa Tunnel on Oahu). In addition, important auxiliary data - seafloor currents and basic meteorological data (wind speeds and sea conditions) - will be obtained to help with the understanding of observed variations in ambient noise level.

Four major instrument systems will be used to carry out the deployment and data acquisition required for the Pilot Experiment effort. The BroadBand Borehole Seismometer System (B^3S^2) is the downhole seismometer with the control electronics and recording system. A brief description of this system can be found in Section 6e of this report. This will be emplaced downhole using the wireline Control Vehicle (CV - see Section 6b) that is fitted with the necessary thrusters and video systems to permit precise placement of instrument systems either on the ocean floor or down an ODP drill hole that is fitted with a re-entry cone. The seafloor measurements will be made with one of two Broad-Band Ocean Bottom Seismometers (B-BOBS). A second B-BOBS will have its sensor package buried surficially beneath the sediments of the seafloor.

Upon recovery of the recording systems in mid-1997 the data will be made widely available to the community via the IRIS Management Center. Quantitative comparisons of the waveforms and ambient noise levels from the seafloor, buried, downhole and island stations will allow important first judgments to be made concerning the relative merits of these four contrasting approaches to the acquisition of broad band seismic data in the world's oceans.

• 5.2.B: CORK-to-CORK Experiments

Plans for a second sedimented ridges drilling program (ODP Leg 169, summer 1996) include refurbishment of the original two CORKs installed in Middle Valley during Leg 139 (1991). These operations will be coordinated such that two "active" CORK-to-CORK experiments are performed. During Leg 139 operations, the local effect of circulating cold seawater in Hole 857D was great; pressure anomalies of over 1 MPa were created in the hole relative to formation pressures. As a result, 10,000 liters/min of cold seawater was drawn down the hole, mostly into a single, 5 m thick zone, until the hole was sealed with a CORK (Becker et al., 1994). Operations during Leg 169 will be sequenced such that Hole 858G is first reCORKed, and then the pressure anomaly in Hole 857D will be restimulated for a period of a few days, by circulating cold seawater and deepening the hole. The resultant pressure anomaly in Hole 857D will be used for active experiments in two ways:

(1) A 1 MPa borehole fluid overpressure is significant with respect to the effective stress in the Middle Valley rift valley environment. Assuming that the rift valley normal faults are in a state of stress near failure, then a large induced pore-fluid pressure anomaly could stimulate microseismicity. This possibility presents a fascinating opportunity to investigate the geometry and mechanism of faulting in this hydrothermally active rift. The experiment will be coordinated with the deployment of an array of ocean bottom seismometers for a several month period that begins before drilling and ends after all Leg 169 operations in Middle Valley are terminated. This OBS deployment will first determine the level of natural microseismicity before drilling, for a baseline against which to then assess the effects of the borehole fluid pressure pulse during and after drilling. The pulse will have a sudden onset, and will last several days before the new CORK is installed in Hole 857D. In addition to monitoring seismicity, formation pressures will be recorded in the reCORKed Hole 858G during and after the pressure "pulse", and in Hole 857D after it is reCORKed, so that pressure changes associated with microseismicity could be detected.

(2) The pressure pulse in Hole 857D will also result in a CORK-to-CORK hydrologic communication test (Figure 5.2-2) to assess the lateral permeability structure between the two holes at a scale analogous to that of the actual hydrothermal circulation in Middle Valley. In this experiment, effects of the pressure pulse generated in Hole 857D will be monitored in the reCORKed Hole 858G 1.6 km away. The speed with which the pulse will diffuse through the capped, permeable basement formation will depend primarily on the hydraulic transmissivity of basement, and the amplitude of the response will constrain the storage capacity of basement. At the high permeabilities previously measured (Becker et al., 1994), the time constant for a radial distance of 1.6 km is roughly 3 days; a maximum pressure of roughly 150 kPa should be observed (and easily resolved by the pressure gauge) at the monitoring CORK in Hole 858G.

INSERT FIG. 5.2-2 HERE

Fig. 5.2-2 Schematic of the CORK-to-CORK hydrologic communication experiment planned for 1996 ODP operations at Holes 857D and 858G in Middle Valley, Juan de Fuca Ridge.

• 5.2.C: Downhole Geochemical Monitoring

Spatial and temporal variability of fluid compositions are obvious indicators of active fluid flow processes, so there exists considerable interest in developing long-term downhole geochemical monitors. Long-term monitoring of fluid compositions is also of great interest in seafloor observatory efforts such as the RIDGE ROBE program and HUGO, so this is certainly one area in which technology development can be shared. There are any number of laboratory-grade ion-sensitive electrodes, but these are generally not stable over long periods of time without periodic recalibration, and therefore are not immediately suitable for long-term deployment in remote seafloor or borehole observatories.

An alternative downhole sampling/monitoring approach has recently been pioneered by H. Jannasch (Stakes et al., 1995) and M. Kastner, in conjunction with a CORK deployed in 1994 in the Barbados accretionary prism. The prototype device incorporates an osmotic fluid pump and long (≈1km) teflon microtube to continuously sample from a zone of interest - the intersection of a fault zone with the hole - over periods of years. When the device is recovered, the fluid in the tubing will be sub-sampled to study the temporal variability of the fluids presumably entering the borehole from the fault zone. The prototype sampler is a self-contained unit that was simply attached to the outside of the CORK cable at the appropriate depth, and thus requires recovery of the cable itself. Further developments could include (1) extending the micro-tubing to the CORK seafloor valving, so that samples could be drawn at the seafloor, and (2) incorporating certain ion-sensitive electrodes with calibration fluids at the osmotic pump, which could also be moved to the seafloor for accessibility.

5.3 Examples of Planned Experiments

• 5.3.A: Hole-to-Hole Seismic Experiments

Crosshole seismics have the potential to reveal details of structural heterogeneity that are not defined through simple one-dimensional borehole measurements or offset vertical seismic profiles. Crosshole seismics can be run at frequencies from VLF (2-100Hz) to sonic (1KHz-10KHz). In the seismic (long wavelength) case, a source is located along the strike of a pair of boreholes. The formation is imaged by modeling changes to the signal seen as it passes from one borehole to the other. At higher frequencies, a source may be located in a borehole at different levels, shooting directly to a string of receivers in other nearby boreholes. Stability of the borehole observatory experiments, decoupled from a surface ship and noisy drillpipe, allows effective signal stacking techniques to be employed. Results in both cases are normally analyzed in a tomographic sense. Resolution increases and range of propagation decreases with increasing frequency. Generally, spacing of holes is limited by the depth of the holes, with distance between holes not to exceed twice borehole depth.

• 5.3.B: Hole-to-Hole Fluid Experiments

All determinations of crustal or sedimentary hydraulic characteristics in DSDP/ODP holes have been made on single holes over relatively short periods of time. As a result, packer tests conducted from the drillship typically provide information on hydrogeologic properties within a few diameters of the drill hole. Although submersible-based pump tests at CORKed sites can extend the tested section to several meters from the borehole (Screaton et al., 1995), a significant portion of the section may still include drilling disturbance. More realistic results can be obtained in hole-to-hole or hole-to-seafloor studies, where the disturbed section becomes an inconsequentially small proportion of the experimental geometry.

Standard terrestrial hydrogeologic tests employ a test well that is pumped, and one or more passive observation wells. Translation of this plan to the sedimentary section in the marine environment would require installation of paired, sealed (CORKed) boreholes. The advantage of such a configuration is that the boreholes could be positioned not only to monitor pressure effects, but also to accommodate geochemical tracer studies, that could document elemental transport through sedimentary aquifers. An interesting benefit of such a deployment could result if the first hole were drilled and allowed to equilibrate. That observation well could then be programmed to monitor conditions induced by drilling the second hole, to quantify the effects that standard drilling practice has on the fluid regime.

On a much larger scale, R. Von Herzen (Section 10) has proposed regional hole-to-hole or hole-to-seafloor experiments to delineate the hydraulic properties of the upper oceanic crust. The experiments rely on the common occurrence of high permeability ($\sim 10^{-12}$ to 10^{-13} m^2) upper crust (<200 m depth below sediment/rock interface) which lies between low permeability (10^{-16} to 10^{-18} m^2) deeper crust and pelagic sediments. Furthermore, packer and flow meter tests at Sites 504 and 395 have demonstrated rapid downhole flow under borehole-to-formation pressure differentials probably induced by drilling. Under these conditions, modelling suggests that for a permeability of 10^{-13} m^2, the hydraulic diffusivity of the upper crust (~6 orders of magnitude greater than the thermal diffusivity) will allow the pressure field to diffuse outward from an open borehole. A second, sealed (CORKed) borehole that penetrates the upper crust and is positioned ~1 to 4 km away, should record the pressure response after about ~1 to 12 months, respectively. Over this same time period, the vertical pressure gradients in a thin (few tens of meters) sediment layer above the crust will change in response to this altered basal boundary condition, and can be measured by seafloor pore pressure instruments deployed as a function of distance from the borehole. The initial test of this experimental configuration will come on ODP Leg 169 (see Section 5.2.B).

• 5.3.C: RIDGE Observatories

Long-term seafloor observatories including both seafloor and borehole instruments have comprised an essential component of the RIDGE Program since its inception at a 1987 workshop. Delaney et al. (1987) proposed the Long-term Ocean Bottom Observatory (LOBO), incorporating several instrumented boreholes, to monitor temporal variability in a wide variety of processes operating along a ridge crest.

More recent RIDGE documents have placed less emphasis on the borehole component of RIDGE observatory experiments (now known by the acronym ROBE), probably owing to the difficulties ODP has experienced in developing reliable drilling techniques for unsedimented ridge crests. Nevertheless, the current RIDGE Science Plan emphasizes the tie to ODP as follows:

"RIDGE activities are also closely linked to the international Ocean Drilling Program (ODP). The investigation of magmatic and hydrothermal processes at mid-ocean ridges was identified as an important thematic objective for ODP by both COSOD I and II, and the development of the necessary technology to drill in such environments has been a top priority for the engineering efforts within ODP. Although the drilling system required for zero-age crust is not yet operational, success has been achieved in a sedimented ridge hydrothermal region (Middle Valley, Juan de Fuca Ridge) using conventional techniques. Drilling can be viewed as one component of a broader, longer-term investigation of mid-ocean ridge processes that will involve detailed surface geological mapping and sampling, geophysical experiments, and concurrent monitoring of magmatic and volcanic activity, hydrothermal output and water column chemistry."

A very important aspect of the ODP success achieved in Middle Valley included the emplacement of the first two CORKs (the two units that are to be refurbished for the CORK-to-CORK experiment described in section 5.2 above). Thus, the basic CORK experiment monitoring subsurface temperature and pressure may be considered the first generation borehole component suitable for a RIDGE ROBE site. Further developments highly desirable for a full-fledged ROBE borehole observatory would include additional subsurface instruments such as seismometers, tiltmeters, flowmeters, and geochemical sensors, as well as the capability to perform active sampling and formation testing as described in the following section.

• 5.3.D: Real-Time Experiments

Telemetry of data between borehole observatories, shore-based stations, surface vessels, or satellites holds the promise of active experimentation in real time. In a few locations, cable connection between the borehole and a land-based facility may be possible, that will allow direct two-way communication with, and power transmission to, the instruments. More commonly, however, an acoustic link will provide data transmission only. Initially, data will be recovered and simple experiments conducted by interrogation/instruction from a surface vessel. Ultimately, however, links to buoys and satellites should provide real-time, two-way communication to land-based investigators (although, initially, at considerable cost).

The importance of real-time data recovery and instrument control, however, comes with the ability to monitor in-situ conditions and perform experiments appropriate to those conditions. For example, at a borehole observatory installed to monitor fluid flow on an accretionary prism, pore-pressure can be expected to fluctuate over periods that range from hours to years. Because preliminary evidence indicates that permeability (and therefore flow) is pressure-dependent, an optimal experiment would combine long-term passive monitoring of pore pressure with hydrogeologic tests and geochemical monitoring/sampling at pressure and flow extremes. If the observatory were equipped with a motorized metering valve and flow meter, constant flow discharge tests could be performed remotely under high and low pressure conditions to document variability in permeability and calculate flow rates. Simultaneously, downhole geochemical sensors or samplers could be activated to record the fluid composition associated with episodic flow events and intervening periods of re-equilibration. In another scenario, an observatory optimally deployed on an active ridge crest could provide real-time data on an eruptive event. Integral seismometers, strain gauges, tilt meters, and precision pressure transducers would document movements associated with magma emplacement and extrusion. It is unclear at this time what the subsurface manifestations of an eruptive event are, or over what length of ridge axis they extend, but during an eruption observatory scientists would certainly measure pore pressure fluctuations, and changes in downhole temperature that might indicate fluid flow related to deformation or enhanced thermal convection. Geochemical sensors would be activated to document seismic- or extrusion-related changes in subsurface fluid composition. If an integrated flowmeter and motorized valve were part of the sealed borehole installation, rates of fluid circulation associated with an active volcanic phase could be determined and compared with circulation during quiescent periods.

As instrumentation advances, borehole observatories will undoubtedly be augmented by seafloor sensors, using acoustic local area networks (ALANs). In the experiments described above, one could envision seafloor piezometers, geochemical sensors, transmissometers, geophones, and other instruments that would document seafloor manifestations of subsurface conditions. These instruments might be deployed long-term (e.g., at known fluid venting sites), or they might be emplaced only as needed (e.g., during an eruptive event) by wireline or ROV.

• 5.3.E: Time-Series Studies

Studies are needed of long-term inter-relationships between tectonic and hydrogeologic events, both periodic and transient. In convergent margin settings, instrumented boreholes will include stress-strain tools (see K. Brown, Section 10), pressure and temperature sensors, and tilt meters in isolated sections of the borehole. In conjunction with seismic recording, this sensor array will detail hydrologic response before and after seismic activity, as well as pre- and post-seismic deformation or aseismic slip. It may be possible to locate several packages of these sensors in satellite locations (shallow boreholes) interconnected to a central observatory. An area network with distances between stations on the order of kilometers would be able to detail deformation across separate thrust slices in an accretionary prism or across a median valley. Addition of geochemical sensors will indicate changes in fluid flow regimes associated with either steady-state or episodic deformation.

• 5.3.F: Gas Hydrate Experiments

Marine gas hydrates are potentially an immense reservoir of methane and other gasses that may have a significant impact on future energy resources, marine landslide hazards, and sources of atmospheric greenhouse gasses (Kvenvolden and Barnard, 1983; Kvenvolden, 1988; Hand et al., 1984; Paull et al., 1991). Their presence in marine sediments is inferred from seismic records of bottom-simulating reflectors (BSR's) and they have been recovered in cores during DSDP and ODP drilling. The exact relationship between BSRs and hydrates, however, is not well understood.

There is a distinct need for long-term observations and development of new methods for studying gas hydrate-cemented sediments in situ. Several approaches may be considered which include both conventional and new technology. Repeated borehole seismic and acoustic experiments will determine the recovery of hydrate layers in the vicinity of the borehole after drilling has terminated and the system has been re-sealed. Chemical sensors or samplers external to borehole casing may simultaneously monitor the composition of pore fluids as they change during re-establishment of the hydrate layer, as well as describe distribution of various species within established hydrates where they can be accessed from borehole observatories.

• 5.3.G: A Permanent Globally-Distributed Ocean Seismic Network

The Ocean Seismic Network program is dedicated to the objective of emplacing an optimally distributed set of permanent broadband seismic observatories around the global ocean floor.

Existing plans within the US for progress with OSN call for a three phase approach. In Phase 1 pilot experiments are proposed to address the fundamental physical problems of sensor coupling and noise, and devise solutions to the technical issues of power, data retrieval and system reliability on the multiple-year time scale. These plans have been described in Section 5.2.A of this report. In Phase 2, a small number of prototype observatories are installed that immediately begin contributing data to the seismological community, but which also, through the collection of auxiliary data sets (e.g. currents, wind speeds, seafloor seismic sensors) and through their contrasting locations (varying sediment thicknesses, proximity to coastlines) provide new understanding of the optimal design and siting of ocean floor seismic observatories. The most recent set of plans for the location of these systems is shown in Figures 5.3-1-3 (Purdy and al., 1995). These figures illustrate six stations identified as Phase 2 sites, two in the north-west Pacific, one in the Central Atlantic and three in the eastern and central Pacific. In Phase 3 the complete network of ~26 stations is installed and efficient schemes for the long-term support and maintenance of the instrumentation are devised. This is conceived at all stages to be an international effort, with each country contributing independently their knowledge and expertise to each Phase.

INSERT FIG. 5.3-1 HERE

Fig. 5.3-1Existing and planned island sites in the Atlantic Ocean by Federation of Digital Seismographic Networks (FDSN). Circles of 10º radii indicate the 128-station, uniform coverage goal. Gray areas surrounding the continents indicate oceanic coverage from coastal continental sites (not plotted). From Purdy and al. (1995).

INSERT FIG. 5.3-2 HERE

Fig. 5.3-2 Existing and planned island sites in the Indian Ocean by Federation of Digital Seismographic Networks (FDSN). Circles of 10º radii indicate the 128-station, uniform coverage goal. Gray areas surrounding the continents indicate oceanic coverage from coastal continental sites (not plotted). From Purdy and al. (1995).

INSERT FIG. 5.3-3 HERE

Fig. 5.3-3 Existing and planned island sites in the Pacific Ocean by Federation of Digital Seismographic Networks (FDSN). Circles of 10º radii indicate the 128-station, uniform coverage goal. Gray areas surrounding the continents indicate oceanic coverage from coastal continental sites (not plotted). From Purdy and al. (1995).

It is likely that all of these sites will require ODP drill holes if their sensor systems are to be optimally emplaced. No universal plan exists for methods of data retrieval and power supply. The supposition is that the best solution to these issues will vary depending upon the station location. For example, plans are already in place to operate the Phase 2 Central Pacific site (between Hawaii and California) using an abandoned AT&T telecommunications cable that will provide power and real time data retrieval (the H2O program). It is possible that the Equatorial Pacific site could take advantage of the proximity of the TOGA-COARE buoy array to provide limited real time satellite communications (perhaps for state-of-health information). The Phase 3 Southern Ocean sites are, however, so isolated that internal data recording with annual or bi-annual visits by a research vessel to replace power sources probably will be required. Although the primary function of these sites will be the support of the downhole seismometer observatory, it is obvious that the logistics required to support this effort can, at minimal additional cost, support the collection of other valuable data sets, not necessarily requiring downhole sensors. One important example is geomagnetic observatories.

Geomagnetic observatory data serve a diverse research and commercial user community. For example, vector geomagnetic field data with good baseline control and evenly distributed over the globe are essential for main field and secular variation modeling, and enter into studies of core-mantle boundary processes. Measurements of the time variations of the field are essential for induction studies and space physics investigations of individual magnetic events. Finally, magnetic activity indices are derived from globally distributed observatories, and are essential to the power and telecommunications industries in mitigating geomagnetic interference with their services. The possible sources of noise for a seafloor magnetometer include hydrodynamic, seismo-acoustic, and long-term tilting. All of these might be reduced by installing a magnetometer in a borehole, although data pertaining to these questions are lacking at present. However, borehole installation would require the use of uncased holes or non-magnetic casing would be essential.

6. Status of Post Drilling Borehole Instrumentation

6.1. ODP Borehole Re-entry Sites

The present status of DSDP/ODP reentry holes suitable for consideration for BOREHOLE experiments is summarized in Table 6-1. This table was drawn from a longer table provided by ODP in which all reentry holes were organized according to the feasibility of further drilling. In reorganizing this information, we have attempted to categorize the reentry holes by their utility for present or future experiments, and have culled most of the reentry holes which are not considered possible candidates for experiments.

Table 6-1. DSDP/ODP holes suitable for post-drilling science.

INSERT TABLE 6-1 HERE

Two important observations can be made from Table 6-1: First, the number of reentry holes suitable for experiments is fairly small (< 30), and second, over half of the best prospects have already been used or are in use for such experiments. The latter demonstrates the community interest in BOREHOLE-type experiments dating back to the late legs of DSDP. The former demonstrates that the essential resource for post-drilling experiments - suitable reentry holes - is quite limited. There are a number of reasons for this, the most significant being the commitment of both funds and drillship time required to establish a reentry hole. An important recommendation of the BOREHOLE Workshop was that JOIDES and ODP be encouraged to establish as many full-fledged reentry holes as possible, as these are an important legacy for future experiments. The full potential for these legacy holes may not be realized or even imagined at the time of drilling. The JOIDES Planning Committee recently seconded this sentiment, by endorsing the following consensus at its August, 1995 meeting:

"Cased, reentry holes have great potential scientific value for seafloor observatories, future drilling, etc. In the past, the decision whether or not to complete a scheduled reentry hole with casing has been left to Co-Chief Scientists. Rather than lose potential important cased holes to expediency, PCOM directs panels, especially thematic panels, to identify potentially important "Legacy Holes," to be noted in the annual drilling prospectus. PCOM will review the list and decide whether to mandate casing of a possible "Legacy Hole."

Finally, it should also be noted that most BOREHOLE-type experiments will indeed require a reentry hole, but some may not, and might instead be deployed on a "drill-in" basis in a single-bit hole hole. Such a method was developed for the deployment of a seismometer in Hole 581C during Leg 88 and is described in Byrne et al. (1987).

6.2 Borehole Re-entry Capabilities

There are two approaches to reentry of an ODP drillhole that do not require use of the drillship: (a) Wireline reentry from a standard oceanographic research vessel, and (b) reentry using a submersible. Both approaches have been demonstrated to work on ODP boreholes.

- **6.2.A: Wireline Re-entry.**

A wireline reentry system was developed in 1988 at the Scripps Institution of Oceanography/Marine Physical Laboratory to install and retrieve borehole seismometers and their associated recording packages from seafloor boreholes. With Navy funding, the system was successfully used at DSDP hole 534A in 1989 (Spiess et al., 1992).

Two major elements for wireline installation and recovery are the ship itself and the Control Vehicle (CV; Fig. 6.5-1). Each of these maneuvers in a horizontal plane to suspend the borehole payload precisely over the hole, with the ship's winch controlling the vertical position of the load. This geometry implies independent propulsion systems and precise navigation. In the case of the ship, the navigational reference is provided by the satellite-based Global Positioning System. With use of the "P" code, in which the pseudo-random noise signal transmitted from the satellite can be correlated with a stored replica in the receiver, the ship's position can be determined, second by second, with accuracy of a few meters. The navigational reference for the Control Vehicle is a local sea floor long baseline acoustic transponder system, which can locate the CV and reentry guide probe beneath the borehole instrument with meter accuracy every few seconds. Propulsion for the ship (e.g., Melville, Thompson, Knorr, Revelle) is provided by a diesel-electric powered set of three trainable, variable speed screws. With control by computer or very attentive ship's personnel, some reference point on the 80 m long ship can be held within a 25 m radius circle for a prolonged period. Similarly, with a pair of electric-hydraulic driven thrusters mounted at right angles on the Control Vehicle, a resultant force in any direction (compass or relative) is achieved, and the payload can be maintained over the hole for reentry, or to engage the recovery hook to pull a payload out of the hole.

The Control Vehicle fulfills an additional function of accepting the high voltage (2300 V AC) sent down the wire from the ship and converting it appropriately to drive its propulsion units and to power the electronics both in the vehicle itself and the instrument package below it, e.g. a seismometer recording package, borehole seismometer and TV and acoustic reentry lead-in unit. The CV also acts as a telemetering relay station between the equipment below and the ship above.

The original system, using a less maneuverable Control Vehicle than that currently available, conducted a 1989 operation to probe two mud-plugged holes (417D & 418A), and then carried out a full installation, monitoring and recovery operation at hole 534A in 5,000 m of water, working from the R/V Melville. A new Control Vehicle has been used in several operations over the past few years: (a) to carry out a transponder-navigated gravity coring operation on the Carolina Rise in October, 1993; (b) to inspect the reentry cone at drill hole OSN-1 in January, 1994; and (c) to reoccupy seafloor benchmarks (1 m diameter) with a precision pressure gauge for geodetic monitoring of the Juan de Fuca Ridge in August, 1995.

• 6.2.B: Re-entry Using Manned Submersibles

A co-operative effort in France between INSU (Institut National des Sciences de l'Univers), IFREMER and IPGP (Institut de Physique du Globe de Paris) successfully completed the deployment and recovery of a broadband seismometer system in Hole 396B on the flanks of the Mid-Atlantic Ridge in early 1992 (Montagner et al., 1994a,b). The seismic instrumentation was installed in the borehole using the French submersible Nautile and an IFREMER re-entry logging system called NADIA, the primary components of which are identified in Figure 6.2-1. Note that this is the system that was used in the 1989 DIANAUT program described in Section 5.1.C above.

INSERT FIG. 6.2-1 AND CAPTION HERE
(Note: Fig. 6.2-1 FIGURE = Fig 1 on page 9 of the Winter 92/93 OSN Newsletter; I do not have - B. Carson**)**

• 6.2.C: Wireline Logging by Borehole Re-entry

Many logging tools have a larger diameter than the internal diameter of the JOIDES Resolution drill pipe (10.5 cm) and bottom hole assembly (9.7 cm), and have yet to be deployed in ODP holes. These instruments include existing, state-of-the-art tools that are used commonly in industry and could be transferred directly to scientific applications if they were deployed by wireline re-entry. The evolution and structure of the oceanic crust, its lateral heterogeneity and anisotropy, and high-resolution detail of borehole features, may be investigated using borehole gravimetry, enhanced formation microimaging, deep azimuthal resistivity imaging, and formation fluid sampling. For example, the Schlumberger Formation MicroImager (FMI) can approach 360 degree borehole wall coverage. The Azimuthal Resistivity Imager (ARI) can be used to measure deep formation resistivities 360 degrees around the borehole, providing unique measurements of lateral heterogeneity at a length scale of meters. The Modular Dynamic Formation tester (MDT) is designed to perform pressure tests and extract fluid samples over vertical intervals that are isolated using packer elements. Additionally, any of several extant borehole gravimeters could be deployed to make independent, high-resolution measurements of bulk density without the use of active nuclear sources.

6.3 ODP Instrumented Borehole Seals (CORKS)

The primary objectives of the CORK experiment are to stop the exchange of formation fluids and ocean bottom water by sealing an ODP hole, such that sensors sealed into the hole can be used to monitor in situ temperatures and pressures over long time periods, and to assess natural hydrogeologic processes after recovery from the disturbance induced by the drilling process. As presently configured and deployed, each CORK requires a dedicated reentry hole cased to an appropriate depth. The geometry of sealing a reentry hole/casing system implies that the experiment will provide useful data only if the CORK seal corresponds to some analogous natural seal, i.e., when the casing penetrates a less permeable section overlying a more permeable formation of interest. This is just the geometry that holds for most ODP holes drilled into sedimented seafloor, since ocean sediments are generally less permeable than the underlying oceanic crust. Good examples of appropriate locations for CORK experiments would be sedimented ridge flank hydrothermal systems, sedimented spreading centers, and accretionary complexes where less deformed sediments overlie sedimentary formations with permeabilities enhanced by deformation and faulting. However, it should be noted that a CORK may be less appropriate for a hole penetrating only formations hydraulically open to the seafloor, as might be expected during shallow drilling at an unsedimented ridge crest.)

Of the first 6 CORKs deployed in 1991, 1992, and 1994, 5 were fielded by a Canadian/American team and the 6th was deployed by a French team. Six more CORKs are planned for 1996 ODP operations, all from the American/Canadian team. The following description of the experiment pertains to the Canadian/American design; the French design differs principally in the sensor string and data logger.

The Canadian/American team began developing the CORK experiment in 1989. While the CORK instrumentation has undergone considerable evolution since original conception, the basic configuration has held to the initial philosophy of keeping the experiment as simple as possible to maximize the likelihood of success. The present baseline CORK system (Figure 6.3-1) now includes:

(1) A seal inside a slightly modified ODP casing string that prevents either drawdown of ocean bottom water into the formation or expulsion from overpressured formations. The seal and mechanical latches are designed to withstand maximum differential pressures up to several MPa, as might be possible in holes in accretionary complexes.

(2) A programmable data logger with sufficient battery and memory capacity to record up to 14 variables at typical intervals of 10 min to 1 hr for several years, with an underwater RS-232 connection for data retrieval and reprogramming with an ROV or submersible.

(3) A 20-conductor, 10-thermistor cable, that allows long-term determination of temperatures spaced at pre-selected intervals down the hole beneath the seal. The cable employs a center strength member and outer cover made of Kevlar. The inherent flexibility of the Kevlar cable design has proven to be essential under real deployment conditions when unpredictable hole depths or hole conditions have required shortening of the cable in the field. Such shortening can be accomplished simply by folding the cable over at appropriate positions and binding the resultant package together, without need for underwater connectors or electrical reterminations prone to long-term failure.

(4) Two pressure gauges, one above the seal and the other in the sealed hole, for long-term records of pressures in the sealed hole against a hydrostatic, tidally-influenced reference. The attenuation and phase lag of tidal signals recorded in the sealed hole can be used to estimate hydrologic properties of the sealing upper layer. We use two accurate absolute gauges rather than a differential gauge, in order to avoid introducing any hydraulic lines through our electronics pressure vessel, which would be required owing to the physical constraints imposed by initial deployment of the data logger down the inside of the drillstring.

(5) A valved port at the seafloor through which controlled "production" tests of the sealed formation can be carried out, during which differential pressure and flow rate can be monitored and borehole fluids can be sampled. In our initial CORK deployments, we attached 1/2" diameter teflon tubing to the cable for the purpose of fluid sampling. However, this approach has never proven fruitful, because of negative differential pressures in the Middle Valley CORKs and because of great difficulties in deploying the tubing given the poor hole conditions at accretionary margins. A second method for fluid sampling is now under development, using a self-contained osmotic sampling device attached to the cable (and first deployed in the Barbados CORK experiment).

INSERT FIG. 6.3-1 HERE

Fig. 6.3-1 Schematic view of the instrumented borehole seal (CORK) assembly installed in a reentry cone and casing. From Davis et al. (1992).

Further details regarding specifics of the instrument are given by Davis et al. (1992). CORK data are downloaded and the logger reprogrammed by establishing an underwater RS-232 connection using the "top hat" device shown in Figure 6.3-2. This device has been used successfully many times, establishing a connection to a laptop computer in a submersible, or in one case to a shipboard computer via the ROV ROPOS. An acoustic modem has been fabricated to retrofit CORKs so that data may be recovered without use of a submersible or ROV.

INSERT FIG. 6.3-2 HERE

Fig. 6.3-2 Schematic of the self-centering "top hat" connector that establishes an underwater RS-232 link to enable CORK data recovery and reprogramming. From Davis et al. (1992).

6.4 Fluid Sampling

Sampling pore fluids after drilling is a difficult task. Immediately after completion of the hole, it is filled with circulated fluid, which penetrates the formation to a distance that depends on overpressures generated during drilling, ambient local pore pressure, and the permeability of the formation. As a result, the use of packers and "active" fluid samplers to isolate a portion of the hole, evacuate contaminated fluid, and then pump uncontaminated pore water into a container, may not be feasible within a reasonable period of time. At some sites (primarily convergent margins) in-situ pore pressures are super-hydrostatic and one could expect that, given sufficient time, an open borehole would purge itself of drilling-related fluid. Hence, in those settings, a "passive" sampling strategy may be appropriate, where fluids are sampled in the borehole by traditional methods. If the borehole purges very slowly, repeated sampling of the evolving pore waters can yield, by extrapolation and inference, the nature of the formation fluids. In holes drilled into ocean crust, sub-hydrostatic pressures induced by cold drilling fluids result in down-hole flow and make sampling of formation fluids, either actively or passively, virtually impossible (Mottl and Gieskes, 1990). Only when these holes are sealed (as at Site 858G) and thermally equilibrate, are super-hydrostatic pressures re-established (Davis and Becker, 1994).

To date only passive sampling has been carried out during borehole re-entries, whether with the drill ship (Magenheim et al., 1992; Magenheim, 1995; McDuff, 1984; Mottl and Gieskes, 1990), or by means of tools lowered by wireline or ROV/submersible re-entry vehicles (Gieskes and Magenheim, 1992). The latter study utilized a borehole fluid sampler that fills up to four evacuated chambers, so that samples can be collected at different sub-bottom depths. However, to establish a temporal sequence, multiple re-entries must be made. A different approach to long-term sampling of borehole fluids has been to couple an osmotic pump to a microtubing sample chamber (MBARI-Osmosampler; Stakes et al., 1995), as described above in section 5.2.C. The instrument deployed at Site 949C draws a fluid sample from the borehole over a one-year interval, so that the temporal evolution in composition can be determined. Initial results from Site 892 suggest that such a sampling strategy may dictate that the hydraulic port on the CORK be left open for an extended period (depending upon the flow characteristics of the overpressured hole) so that the drilling fluid can be efficiently purged.

6.5 Downhole Broadband Seismic Instrumentation

A prototype broadband borehole seismograph system (Orcutt and Vernon, 1995; Stephen et al., 1995) has recently been developed that is suitable for use in the Ocean Seismic Network pilot experiments described earlier in this report (see Section 5.2.A).

The major components of the system are illustrated in Figure 6.5-1. The broad band borehole package was developed and tested at the Institute of Geophysics and Planetary Physics (IGPP) at the Scripps Institution of Oceanography (SIO). The recording and telemetry systems were designed and produced by Woods Hole Oceanographic Institution, and the wireline Control Vehicle (CV) for deploying and recovering the system was developed at the Marine Physical Laboratory (MPL) at SIO. The two major underwater packages are the Bottom Instrument Package (BIP), and the Broadband Borehole Seismometer (BBS). The Control Vehicle maneuvers the array during the reentry operation, maintains station during shipboard recording, and telemeters all power and data between the seafloor and the surface on the UNOLS standard 1.73 cm (0.68") coaxial cable. The primary task of the BIP is to house the electronics and power supplies used in the autonomous recording operation on the seafloor. The sonde consists of the Teledyne KS54000 broadband, three-component seismometer and digitizing system, and the camera and lights necessary for the reentry operation.

INSERT FIG. 6.5-1 HERE

Fig. 6.5-1 Seismometer deployment sequence. The first frame shows the relationship between the Broad Band Seismometer (BBS), the Bottom Instrument Package (BIP), the Control Vehicle (CV) and the tending ship. In (a) the configuration as shown is lowered to the reentry cone. In (b) the acquisition and recording package are shown in the cone with a slack electromechanical tether attached to the CV. In (c) the CV has been divorced from the BIP and the B^3S^2 records independently for 3 months. In (d) the CV returns to remove the BIP and BBS from the cone and hole. From Orcutt and Vernon (1995).

The wireline re-entry system is described in Section 6.2.A. In a typical deployment scenario, the borehole is located using the research vessel’s dynamic positioning system, the Control Vehicle’s sonar and the TV camera on the bottom of the sonde. The borehole equipment is lowered into the hole and the video channel is switched to the TV on the BIP to monitor the landing of the BIP in the re-entry cone. The CV then hovers around the cone while borehole operations are carried out from the laboratory on the ship. Operators on the research vessel activate the upper and lower clamps, then unlock the seismometer masses and finally level the seismometers. Data are continuously telemetered to the ship and recorded on board. Operations continue in this mode for one or two days to monitor the status of the sonde as it settles. Ambient noise levels during this period are recorded on the vessel. When satisfactory operation has been confirmed, the soft tether from the BIP to the Control Vehicle is cut and the CV recovered. The acquisition procedure continues until either the end of the experiment, as defined by a pre-determined time, is reached, the power supply is expended or the recorders are full of data. The sonde then locks the seismometer masses and awaits recovery by the Control Vehicle.

7. Technical Challenges Unique to Borehole Installations

7.0 Introduction

There are many technical challenges to be overcome before borehole observatories become routine observational tools of marine geology and geophysics. Many of the needed innovations are not unique to borehole observatories, but rather are common to the entire spectrum of proposed seafloor instrumentation schemes. Such developments include sensors, data telemetry (both to access data recorded and to send command and control instructions), data formats, power supplies, and accuracy of timing. These issues have been addressed in some detail in Montagner and Lancelot (1995). Data telemetry options include direct cable links to land for appropriate locations either near shore or near old telecommunication cables, limited satellite links (limited presently by cost), and data storage for up to a year with retrieval by visiting ships of opportunity. Power will come through cables where direct links are feasible, or from renewable or replaceable power packs in remote locations. Data formats and methods of maintaining accurate timing amongst multiple stations are related issues having to do with identification and acceptance by the community of a standard at some time in the future. Description of these general issues will not be repeated here, rather emphasis is placed on the problems specifically related to the post-drilling instrumentation of boreholes. These unique challenges can be considered in three categories:

7.1 Emplacement of Instruments

The most fundamental component here is the need for a delivery system to transport the instrumentation from the research vessel into the seafloor borehole. Fortunately, substantial progress has been made on this issue over the past five years as the research community increasingly understands the inefficiencies associated with the use of a high-cost drill ship for instrument emplacement. The development of a wireline control vehicle in the US specifically for the purpose of downhole emplacement of instruments is described in Section 6.2.A. A French program using a submersible based re-entry system dubbed NADIA has also been used successfully. Therefore it is clear that deployment can be effected. The fundamental first steps have been taken that establish wireline re-entry of ODP boreholes in the deep-ocean as a practical and achievable goal.

But transportation of the instrumentation from the sea surface to the seafloor is only part of the ‘emplacement’ challenge - depending upon the nature of the sensor system - seismic, geochemical, etc. - special requirements are associated with the coupling of the sensor to the medium that it is designed to measure. One well-known example of this issue is the problem of coupling of seismometer sensors to the ground motion. Fundamental questions that remain unanswered are, for example: What is the optimum geometry and design of the clamping arms that hold the seismometer in the hole? Should the units be permanently cemented in place, as they are in some cases in continental observatories? What problems would flow in the hole produce? It is probable that systems will have to be designed that can be emplaced by the wireline CV and that allow pre-determined sections of the borehole to be sealed against flow.

7.2 Borehole Design Challenges

Proper planning and design of boreholes slated for dedication as observatories will greatly enhance the possibility of successful long-term observation. Casing and cementation schemes must be employed that will insure both lasting hole stability and close coupling to sub-seafloor formations to avoid situations such as occurred at Holes 417D and 418A, where sediments below casing flowed into the borehole and created obstructions to proper instrument deployment. Additionally, it may be necessary to develop wireline methods to clear older boreholes of sedimentary bridges prior to deployment or before instrument retrieval.

A reliable system needs to be developed that will effectively isolate segments of borehole, cased or uncased, to prevent fluid mixing during post-drilling equilibration and to decouple motion-sensitive instruments such as seismometers or tiltmeters from the effects of fluid flow in the borehole. At the same time, data and perhaps fluid samples, must be able to move to the surface unimpeded by the isolation system.

Hole stability and isolation needs suggest that development of special casing materials will probably be necessary to carry out investigations in sedimentary sections. These adaptations may include instrumented casing (sensors on the outside of the pipe), or perhaps non-conductive and/or non-magnetic casing segments.

7.3 Sensors, Sampling, and Sources

Many geochemical and geophysical sensors applicable to borehole observatories are also appropriate for seafloor installations. The range of new and existing sensors needed for borehole experiments is illustrated by the examples in Section 5 and the contributed abstracts (Section 10). Deployment in boreholes imposes particular constraints on sensor size, temperature tolerance, and long-term stability without recalibration. In particular, maintenance or replacement of sensors and retrieval of samples will require special design or operational provisions in sealed boreholes. Removal or replacement of current CORKs requires the lifting capacity of the drillship, and consideration needs to be given to development of a hydraulic seal that can be deployed and removed by wireline/submersible/ROV.

In traditional continental observatories broadband seismometers commonly are installed in drill holes, and therefore suitably configured sensors are commercially available. The primary engineering modification is that associated with installation in a pressure case and designing suitable clamping and fluid-flow-blocking systems as described in Section 7.1.

Discussions during the JOI Workshop on Wireline Re-entry (Langseth and Spiess, 1987) addressed the particular problem associated with sampling uncontaminated fluids. Two modes of sampling were considered: the "active" mode, which constitutes the use of packers in order to attempt to obtain fluids from the formation directly (for instance by suction into an evacuated chamber); and the "passive" mode of sequential sampling of fluids in the borehole with inference from the data as to the nature of fluids in the formation waters. Though various attempts have been made, essentially all attempts at active sampling have failed to provide formation fluids (Mottl and Gieskes, 1990). Only passive mode sampling has been carried out during borehole re-entries, either with the drill ship (Magenheim et al., 1992; Magenheim, 1995; McDuff, 1984; Mottl and Gieskes, 1990), or by means of tools lowered by other re-entry vehicles (Gieskes and Magenheim, 1992). Compartmentalization of the drill holes could isolate zones of potential advective fluid input, thus allowing passive sampling at discrete intervals (compartments) to yield information on formation fluid compositions and zones of active advection.

8. BOREHOLE Recommendations

If U.S. sub-seafloor research is to move forward in a coherent manner over the next decade, a variety of scientific, technical, and organizational issues need to be addressed. Although scientific initiatives will arise from individual investigators, an integrated support program is needed that includes a significant component for equipment development and testing, as well as funding for particular experiments. Perhaps equally important, a program to advance borehole observatories must be carefully coordinated with the Ocean Drilling Program, and with the international community. In a time of limited budgets, participants in the program must set priorities, share technical information, and coordinate experiments. Given the scientific, technical, financial, and management needs required to advance in situ, borehole science, we are convinced of the necessity for a formal organization of proponents.

We propose formation of BOREHOLE (BOREHole Observatories, Laboratories, and Experiments), an organization to facilitate borehole-related, sub-seafloor science. Although the specifics of the organization should be determined by the participants, we anticipate that it should support (1) scientific and technical initiatives, and (2) a variety of non-technical activities that promote the science. Important science and technical elements of a BOREHOLE program should include:

- fundamental research at borehole-related installations to understand dynamic sub-seafloor processes;
- science and engineering feasibility studies to evaluate techniques, and proposed instruments or observatory components;
- new instrumentation development, including funding for test programs;
- establishment of reference or test observatory site(s) in appropriate marine (and, perhaps, terrestrial) settings for equipment calibration and analysis.

In addition, the BOREHOLE program should provide coordination, management, and planning for a strategic initiative to advance our understanding of sub-seafloor processes. To this end, the program should:

- develop priorities in science and technical objectives among users and participants;
- conduct workshops on science and technical issues to aid development of instrumentation, to discuss scientific objectives and strategies, and to plan long-term experiments;
- provide technical information to the user community

- with JOIDES and USSAC, plan for, and formulate policy on, US positions relative to observatories and experiments;
- coordinate instrumentation and facility development with the ODP Engineering Division and with the continental drilling community;
- develop funding sources for observatories and post-drilling experiments.

The latter objective requires consultation with a variety of agencies interested in seafloor experiments (NSF/ONR/DOE/NOAA/USGS), formulation of a budget to support the scientific, technical, and organizational goals of BOREHOLE (see above), and securement of commitments for the long-term funding required for borehole observatory emplacement and maintenance.

To implement these objectives, we propose the following BOREHOLE administrative structure:

- a Steering Committee of 5-8 members, approved by the Joint Oceanographic Institutions (JOI) Board of Governors. Members of the Steering Committee would serve staggered, 3-year terms, and would direct the activities of the program.
- a Program Director to provide management services in consultation with the Steering Committee, and oversee operation of the program.

Implementation of the BOREHOLE program will require simultaneous activities on several fronts, over the next year. A summary of this report and the intention to establish an organization to promote borehole observatories needs to be addressed to the user community, perhaps in an EOS article. Start-up funds need to be solicited for 1996 Steering Committee meetings, and to convene a workshop for interested users to delineate science objectives, assign priorities, establish initial plans, and discuss the nature of longer-term support for BOREHOLE science.

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10. Participant Abstracts

All participants in the workshop were asked to bring a 1-2 page abstract describing their particular interest in post-drilling sub-seafloor investigations. These short papers are collected here to establish the diversity of scientific objectives and technical strategies being considered to implement the science.

A STRESS/STRAIN OBSERVATORY SYSTEM

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I plan to develop long term observatory systems that will allow the quantification of the coupling between transient tectonic and hydrogeologic events in active plate boundary environments. In particular I am concerned with the coupling between changing states of stress and the hydrogeologic properties of active fault zones. While the type of observatory I am keen to develop will initially be directed at convergent margin processes, the same type of system may easily be adapted to study the active extensional mechanics at oceanic spreading centers. Major gaps in our understanding of convergent margin processes will remain until we can accomplish the measurement of the temporal variation in both the stress and deformation patterns across the full subaerial and submarine extent of subduction systems (with or with out the presence of accretionary wedges). Some of the major themes that remain to be addressed include the following: (a) What is the relationship between episodes of aseismic slip at the toe of the wedge, seismic activity at depth, and pulses of fluid flow. For example, are fluids expelled from accretionary wedges by a crack-seal mechanism related to seismicity? (b) How are stress/strain distributed, in a temporal and spatial sense, in the hanging wall of a subduction plate boundary from the back arc to the outer arc rise? One sub-theme within this topic includes the magnitude and nature of the coupling between stress/strain build up and release within the seismogenic and aseismic portions of subduction systems. For example, how do instabilities in one system trigger responses in the other?

My immediate plans include the development of an Ocean Drilling Program (ODP) deployed stress/strain observatory system (SSOS). The purpose of the SSOS system is to quantify the temporal variations in total and effective stress near tectonically and hydrogeologically active fault zones in accretionary wedges so that they can be ultimately coupled to earthquake studies in these active tectonic systems. The initial observatory system would include: (a) A new third party Observatory Stress tool (OST) that would be permanently and directly drilled into the formation below the cased section of the borehole at a depth of ~100-300 mbsf. The tool would be capable of total stress and pore fluid pressure measurements in two mutually perpendicular directions. The tool would also contain a thermistor string (3 -4 thermistors) so that a permanent record of the thermal gradient in the section below the cased hole could be monitored. (c) A precision depth recorder would be deployed in the surface instrument/recording package that would be capable of measuring vertical tectonic related changes in the position of the whole SSOS to a precision of +/-2 mm at full ocean depths. (d) A precision tilt meter. (e) A data acquisition and acoustic telemetry package with sufficient batteries for a five/ten year deployment. The acquisition system would allow the data to be stored and then acoustically transmitted to surface ships on a yearly or by-yearly basis.

The SSOS system could be combined with either a CORK or seismic observatory system. Benthic barrel systems could also, for example, be deployed to monitor changes in fluid venting patterns along the surface traces the local fault zones. Ultimately, the SSOS should form part of a more extensive observatory system in which the interaction between active tectonic systems, hydrogeology, the vent communities could be studied as part of an interdisciplinary OBLISP type program.

IN-SITU OBSERVATIONS OF MARINE GAS HYDRATES AND BOTTOM-SIMULATING REFLECTORS: OPPORTUNITIES AND NEEDS FOR NEW SAMPLING METHODS AND POST-DRILLING MEASUREMENTS

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Marine gas hydrates are potentially an immense reservoir of methane and other gases that may have a significant impact on future energy resources, marine landslide hazards, and sources of atmospheric greenhouse gases. Their presence in marine sediments is inferred from seismic records of bottom-simulating reflectors (BSR's) and they have been recovered in cores during DSDP and ODP drilling programs. However, recent attempts during ODP drilling to penetrate BSR's and directly observe the relation between hydrate cemented sediments and BSR's has had limited success. Furthermore, recovery of hydrate cemented sediment cores requires use of pressure core barrels and some method of making observations on materials preserved at in-situ pressure and temperature conditions.

There is a distinct need for long-term observations and development of new methods for studying and recovering gas hydrate cemented sediments at in-situ conditions. The fundamental goal is direct observation of the distribution of hydrates in sediments at all scales from seismic acoustic wavelengths to high resolution geophysical well-logging methods to, ultimately, the pore scale. These observations will provide accurate calibration of geophysical methods (seismic and well-logging) response to hydrates. The practical goal of this work is quantitative estimates of the amount and distribution of marine hydrates for energy resource and hazard assessment. Such information combined with measurements of in-situ porosity and permeability of hydrate bearing sediments is necessary is necessary to create economic and engineering models of energy resource recovery from hydrate occurrences.

Three approaches should be considered. First, high resolution geophysical methods such as VSP's, borehole-borehole tomography, and well-log imaging methods such as the Formation Microscanner (resistivity tool) and the Borehole Televiewer (acoustic velocity tool), and newly developed nuclear magnetic resonance (NMR) tools can provide improved, indirect direct detection of gas hydrates and free gas associated with BSR's. Second, pressure coring and pressurized core preservation techniques will provide samples recovered at in-situ conditions and allow detailed physical and chemical characterization of hydrate cemented sediments. The most immediate need is development of pressure vessels that allow removal of core samples from the existing pressure core system at in-situ P and T for detailed, post-drilling study. The types of pressure vessels can vary from simple storage vessels to instrumented chambers that allow measurement of physical properties such as resistivity, acoustic velocity, and mechanical strength. Such chambers could include high pressure windows to allow direct optical examination of samples at in-situ conditions. A third, long-term approach is development of new chemical sensor, well-logging, and imaging methods based on fiber-optic technologies to allow direct, unambiguous detection of hydrates. Fiber-optic detectors are available for a sensing a variety of physical and chemical properties of solid, liquid, and gas phases. These methods have the advantage of being mechanically and electronically robust, with sensitive light sources, electronics and detectors located "up-hole" (ideally on shipboard) and only the fibers and an optical sensor head (optrode) located down-hole. Depending on the application, fiber lengths can vary from a few meters to kilometers. Furthermore, there are remote, fiber optic video techniques, analogous to medical endoscopy, that may allow direct video imaging of boreholes.

So, what would I really like to learn with long-term observations or new sampling and sensing methods:

1) What is the real relationship between BSR's and hydrate cemented sediments?
    a. Imaging well-logging techniques run through the BSR.
        i. Immediately after drilling, look at disturbed system
        ii. "Sometime" later, look at "recovered" system, requires borehole re-entry and "stable" hole. Imaging logs run from submersible re-entry system should have highest resolution because of absence of heave motion.
        iii. How does BSR respond to drilling? Does gas flow into hole over time?
    b. Improved sampling
        i. Pressure core barrel with core recovery at in-situ P and T. Remove core from barrel without depressurizing.
        ii. In-situ gas sampling across BSR. What is gas volume and composition in-situ, a) in equilibrium with hydrate and b) below hydrate in BSR?
        iii. What is the change in pore water chemistry in-situ in equilibrium with hydrate versus within and below the BSR?

2) What is the distribution of hydrate within cemented sediments? I know this is another wording of #1, but with emphasis on small scales, ultimately to pore-scale. Requires developing observational techniques for cores recovered at in-situ P and T.

3) What is the porosity and permeability of hydrate cemented sediment and the sediments in the BSR at in-situ conditions? Good opportunity for long-term observation:
    a. Borehole disturbs P and T regime of BSR. How does it respond over time?
    b. We can disturb the P, T regime further through CORK experiments, especially pump-tests. Response of BSR should yield information on porosity and permeability, especially when combined with fluid sampling. Can we sample gases in CORKed holes as a function of time?

GLOBAL SEISMOLOGY AND SEAFLOOR OBSERVATORIES

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The study of the Earth as a geophysical system requires observations and measurements over a wide range of spatial and temporal scales. The science of seismology focuses upon the three-dimensional structure (elastic and anelastic) and tectonics of the Earth and the dynamics of earthquake processes. Seismological studies of the Earth system require (1) a permanent network of seismic observatories with unbiased, uniform, global coverage of the planet for continuous monitoring of earthquake activity and whole earth tomography, (2) portable arrays of sensors deployed at shorter spatial and temporal scales for high-resolution imaging of the crust, lithosphere, and seismic sources, and (3) data collection, management, and archive facilities to provide rapid access to data and to serve the research community and the public.

The Incorporated Research Institutions for Seismology (IRIS) is a not-for-profit consortium of over 80 Universities in the United States which creates, manages, and operates facilities for seismology. IRIS is currently funded by the National Science Foundation through its Earth Sciences Division and by the Air Force through its Office of Scientific Research. IRIS facilities include the Global Seismographic Network (GSN) of over 70 seismic observatories on continents and islands, the PASSCAL (Program for Array Seismic Studies of the Continental Lithosphere) pool of portable seismic instruments, and a Data Management System (DMS) for managing and distributing the more than 1 Terabyte of seismic data collected to date. With its current facilities, IRIS has in place the fundamental infrastructure for the seismological study of the Earth system.

The oceans present unique technological challenges and scientific opportunities for any long-term geoscience monitoring program, and seismology is no different. The seismological study of the Earth system, whether from the continents or the oceans, requires the same basic tools and methods, and has the same underlying scientific justifications. However, the obstacle is the difficulty of the oceanic environment. Routine tasks on land may require major engineering feats to be accomplished in the oceans. Much of the equipment which can be purchased or adapted from existing technologies on land must be specially developed for use on the seafloor. These developments are not uniquely seismological requirements, but rather are broadly geoscientific in scope. Ocean engineering and technology must pioneer any path where the geosciences may wish to tread. Seafloor observatories must be multi-disciplinary in their scope to be cost effective and to meet geoscientific objectives.

The development of seafloor geoscience observatories would substantially benefit global seismology. If the oceans simply were not there, the IRIS program would be siting GSN stations and outfitting PASSCAL experiments throughout the oceanic basins, ridges, & trenches. Whether autonomous or connected by cable to shore; whether the sensors are emplaced in a borehole or buried beneath the seafloor; seismology needs oceanic observatories to reduce the intrinsic bias (both continental and island) in the GSNUs global coverage of the Earth. The development of a oceanic PASSCAL-like capability with broadband seismic sensors for the seafloor deployments would greatly extend and complement a permanent seafloor geoscience observatory program. In either area the IRIS facilities development may serve as a model or a vehicle for a successful approach, and the IRIS Data Management System can easily and extensibly serve as data archive.

DETERMINATION OF FLOW CHARACTERISTICS AND DIAGENETIC EFFECTS IN MODERN ACCRETIONARY PRISMS

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To understand how accretionary prisms dewater, it is necessary to passively monitor the pore pressures that drive flow, and to actively test aquifers *in situ*, to establish their hydrogeologic characteristics (permeability, storativity). At present, with ODP CORKs, we are able to hydraulically isolate boreholes from seawater, log pressure (and temperature) at intervals of seconds to hours, and conduct active formation (pump/slug) tests from submersibles. The initial data suggest that flow is spatially and temporally non-uniform, that it is pressure-dependent, and that modifications to the present CORK design and drilling protocols are necessary to adequately delineate subsurface flow.

Drilling itself perturbates the fluid regime, so we need to incorporate LWD in future development of sealed boreholes. Furthermore, to determine how invasive of the formation drilling fluid is, the ODP should consider emplacement of paired, CORKed boreholes, where an instrumented hole monitors drilling and deployment of a CORK in an adjacent hole. Such paired holes would subsequently be sites of active pump tests, with the preferred configuration of a dedicated observation hole and a pumped hole (rather than the present use of a single CORKed hole as both a test and observation well). Careful consideration needs to be given to experiments in paired holes that incorporate active tracers to definitively characterize zones of high transmissivity.

In addition, ODP CORK sites provide a unique opportunity to conduct experiments on flow modification due to diagenetic reactions. Deposition of hydrocarbon-derived calcium carbonate and gas hydrates clearly modifies the permeability of active flow zones, and these deposits are important elements of the carbon cycle at convergent margins. Yet we have virtually no knowledge of their rates of deposition or decomposition, or of the continuity/volume of these diagenetic deposits within the sediment fabric. Long-term, controlled-discharge experiments into returnable pressure vessels that could be emplaced and retrieved by ROV or submersible, would provide the first controlled experiments that relate rates of flow and pore-fluid chemistry to diagenetic deposition.

SEAFLOOR GEOMAGNETIC OBSERVATORIES

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The distribution of the 200 present-day geomagnetic observatories on the globe is inadequate to record the large scale characteristics of the Earth's magnetic field. For historic reasons, there are numerous observatories in Europe, and to a lesser extent, North America, while coverage is weak in the Southern Hemisphere. Furthermore, the locations of continents and islands precludes good coverage in many parts of the world, notably the Central Atlantic, South Pacific, and Southern Oceans. In addition, island sites often are geomagnetically anomalous, and hence may not serve to adequately round out the global network.

The scientific rationale for a better global geomagnetic network is thoroughly described in a recent report of the Geomagnetic Observatory Task Group to the National Research Council (Heirtzler et al., 1994). In proposing an expanded and better balanced network, the task group identified eight sites where seafloor geomagnetic observatories would be required. The task group further recommended that a workshop be convened to investigate the technical problems of building a seafloor geomagnetic observatory which meets full land observatory standards, including measurement of the absolute field. Such a meeting was held in Woods Hole in mid-November, 1994, and a final report is currently in preparation; a summary of salient points is provided here.

The problems of constructing a seafloor geomagnetic observatory break down into two categories: those specific to geomagnetism (i.e., sensors) and those which are generic to any seafloor observatory effort (i.e., power, installation, and communications). For the former, existing and usually commercially produced technologies are available to measure the vector geomagnetic field variations (e.g., fluxgate magnetometers or suspended magnet variometers), the absolute magnitude of the field (e.g., proton precession or Overhauser effect magnetometers), and ancillary variables like tilt and temperature. The remaining obstacle is a means to measure the absolute direction of the field at a given time with an accuracy of 20 seconds of arc. On land, this is done by determining the angle between the geomagnetic field and a celestial reference using a special type of theodolite; clearly, this is not possible on the seafloor. Two approaches, both of which require significant development, were identified at the workshop. The first of these would require precision acoustic location of a rigid slab on which a geomagnetic observatory is mounted with respect to a fixed transponder network on the seafloor. Using a 100 m baseline, the 20 arc second requirement translates into 0.2 mm location accuracy, which might prove feasible by adapting precision transponder technology to operate at higher (200 kHz) frequencies than at present. The transponder network in which the slab is navigated would have to be surveyed in using co-located 10 kHz precision transponders from a surface vehicle in a similar manner to current geodetic applications of precision transponders. The second approach to measurement of the absolute field direction is under development at the Institut Royal Meteorologique de Belgique, and consists of coupling a declination-inclination fluxgate magnetometer to a nonmagnetic electrostatic gyro- scope. This combination will give the instantaneous absolute angle between the geomagnetic field and true north. However, the electrostatic gyroscope must first be developed.

The remaining issues of power, installation, and communication appear to present no fearsome obstacles, perhaps in large part because the sample rate for geomagnetic data is modest (1 value per minute is typical). An average power consumption of 1-2 watts would be sufficient for all of the combined geomagnetic instrumentation, and could be provided by about US$10K worth of lithium batteries per year. Given the shelf life and reliability of lithium batteries, five year intervals between servicing are certainly feasible. Data could be stored internally and retrieved at infrequent intervals by surface ship, or near real-time data could be transmitted acoustically to a surface buoy and then by satellite to a shore station. The modest data rate (4 Mbyte/year) makes either approach relatively simple. Similarly, installation of a bottom package does not appear to be difficult, although care in its design will be required to minimize hydrodynamic noise.

A seafloor geomagnetic observatory does not require the presence of a borehole unless it can be demonstrated that the borehole environment is markedly geomagnetically quieter than the seafloor one. Based on theoretical considerations this is unlikely, and the technical problems of pack- aging sensors to fit in a standard borehole are not trivial. However, there is much to recommend co-location of seafloor geomagnetic observatories with other seafloor observatories, including sharing of power, communications, and servicing expenses. To that extent, the interests of the sea- floor geomagnetic observatory community meshes with that of the borehole one.

Heirtzler, J.R., J.R. Booker, A.D. Chave, A.W. Green, Jr., R. Langel, and N.W. Peddie, An enhanced geomagnetic observatory network, report of the Geomagnetic Observatory Task Group to the U.S. Geodynamics Committee, National Research Council, Oct. 1994, 64 pp.

STUDYING SUB-SEAFLOOR HYDROLOGY WITH ODP "CORK" BOREHOLE OBSERVATORIES

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Instrumentation has been developed recently that provides a means by which cased reentry holes drilled by the Ocean Drilling Program can be hydrologically sealed and instrumented for long-term monitoring. The instrumentation is referred to as the Circulation Obviation Retrofit Kit, or CORK. Packer seals in the CORK prevent flow of water into or out of holes that would otherwise cause severe thermal and chemical disturbance to the formation drilled. The seals are capable of withstanding both positive and negative differential pressures, both of which have been found to be present in hydrothermally and tectonically active environments. Parameters, including seafloor and formation temperatures and pressures, and seafloor tilt, can be monitored for periods of up to three years during and following the recovery from drilling disturbances. A fluid sampling tube hangs in the hole with the temperature sensor string. This is plumbed through the seal o an external port where differential pressure can be measured, and fluids can be tapped from deep within the hole. The port also allows active hydrologic experiments to be carried out. Data recovery and active experiments have been accomplished via submersible and remotely operated vehicle. The most recent CORK development is a self-contained acoustic module that allows remote communication with the seafloor installations using a surface oceanographic vessel. The link comprises a buffer interface to the observatory instrument, a multiple-frequency-shift-key acoustic modem, and shipboard interrogation software that searches for transmission errors, requests re-transmission of data packets containing errors, and merges data to an error-free state. Error-free data have been received in Cascadia Basin (up to 3800 m slant-range) at a rate of 1200 baud.

Future modifications to the instrumentation are planned which will 1) more than double the memory capacity and active lifetime of the data logger, and 2) permit external power to be applied in order to extend the operational lifetime of the instrumentation beyond 5 years. Additional modifications that would be possible but are not planned include 1) miniaturizing the acoustic data link to allow deployment by the drill ship (c. 89 mm o.d. constraint), and 2) developing a means to monitor pressure at multiple levels. The latter, while considered to be of high scientific priority, is very difficult because of the need to permanently isolate the intervals that include the downhole pressure sensors (via packers, grout, or backfill).

Two CORK units were deployed in 1991 in the sediment-filled Middle Valley sea-floor spreading rift of the northern Juan de Fuca Ridge, where high-temperature (c. 300^{o}C) hydrothermal fluids were found to reside in a regional, sediment-sealed permeable crustal reservoir, and to be driven by high (up to 450 kPa) thermal buoyancy forces through the seafloor locally above a buried basement edifice. Two more instruments were deployed in 1992 in holes drilled into the Cascadia accretionary prism. At one of these holes, transient fluid flow, driven by consolidation of the thickening sediment section, was observed in a thrust fault zone. An additional instrumented borehole seal installation has been completed in 1994 in the Barbados accretionary prism; data retrieval and active hydrologic tests will be carried out there in the Fall of 1995. Other hydrologic experiments using CORK observatories are planned for locations in the northeast Pacific in 1996. These will include refurbishing of two CORKs in the sedimented Middle Valley rift, hole-to-hole hydrologic communication experiments, and a hydrofracturing experiment done while a local ocean-bottom seismometer array is in operation.

CURRENT SEAFLOOR SCIENCE: TECHNICAL CONSIDERATIONS

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Summary of activities

OSS-IV: Long-term instrument installation option: If an instrument package has an outside diameter of less than 4", then it can be installed in an ODP drill hole through the pipe, and left for long-term recording. The Ocean Sub-Bottom Seismometer (DSDP Leg 88, 1981) and the Japanese seismic experiment (Leg 128) were both installed by lowering the instrument package through the drill string and then stripping the pipe from the logging cable. The OSS seismometer package was placed in an uncased hole. A long section of cable was then laid on the ocean floor, and a recording package attached that can be serviced by a standard research vessel. Summaries of the technology can be found in the initial reports (leg 88 for OSS-IV, Leg 128 for the Japanese experiment).

HUGO: The Hawaii Undersea Geo-Observatory is a submarine volcanic observatory funded by the NSF that will have the potential to supply power and real-time data and command telemetry to over 80 experiments on Loihi seamount, an active volcano 35 km off the coast of Hawaii. Each experiment will be able to send up to 2048 samples (up to 24-bit resolution) per second to shore, and use up to 20 watts of power continuously. Experiments will be deployed by submersible and plugged into the HUGO system on the ocean floor. The main electro-optical cable and junction box are scheduled to be installed in the fall of 1995. Interested persons and potential users should contact fred@soest.hawaii.edu for details.

H2O: The H2O Experiment is a proposal to re-use the Hawaii-2 transoceanic cable as a communications and power link to an experiment site approximately mid-way between Hawaii and California. We propose to cut the cable and install a "Junction Box" at this site that will service seismic and other experiments to be installed by submersible or ROVs. This is a cooperative venture between several institutions coordinated through IRIS. Note that a cable similar to H2 that crosses the Juan de Fuca spreading center will probably become available in a couple of years.

Long-term experiments: Notes on data transmission

There are several technological problems associated with long-term experiments on the ocean floor. Most of these, except cost, are solved by cable data and power transmission when distance from shore or to an available cable is relatively short.

It has been proposed that near real-time data access can be accomplished by transmission of data to a surface buoy, and then by satellite to shore. While this method is currently possible, it is only practical for experiments that require very low data rates, as costs of data transmission by satellite are high, currently about $1 per KByte. At this rate, data transmission costs for a simple experiment requiring an average data rate of 10 bytes per second would be more than $315,000 per year.

It is possible to reduce this load for some experiments by storing data on site, and transmitting only data for important times, such as when important earthquake arrivals are expected. This requires considerable on-board storage of data and command capability from shore to the experiment. As an example, a broad band seismometer, taking data at 40 samples per second per axis, with four axes (X,Y,Z, and pressure), and 4 bytes per sample, would require 55MB/day of data storage ($55,000 per day if sent directly to shore), or about $2,300 per hour of data transmitted via satellite to shore.

Observatory science

While there appears to be a need for emplacement of instruments in drill holes for long-term recording of fluids and fluid flow, the case is not as strong for instruments in drill holes for long-term study of physical properties. Instruments to measure long-term strain in ocean boreholes have not been developed (to my knowledge), and there is considerable question whether placing seismometers in deep boreholes in the ocean will increase the signal fidelity and/or signal to noise ratio enough to justify the cost over shallow burial. On land, the major noise source is coupled to the ground at the earth's surface, thus installation of seismometers in boreholes on land can greatly reduce noise levels. In the ocean, however, the major noise sources are waves at the ocean surface, and instruments in boreholes in the deep ocean are not appreciably farther from this interface than instruments buried just below the ocean floor. Seismic instruments in boreholes can also suffer from noise caused by water flow around the instrument, and from poor coupling of the casing to the surrounding rock. While the OSN-1 experiments should provide the quantitative information needed to address these questions, the several experiments accomplished to date point to this conclusion. Arrays of shallow (even <20 m depth) holes in hard rock at spreading centers would likely be excellent sites for installing seismic sensors, and they would not need to be cased or coned to be reoccupied.

Hole placement. There are currently very few DSDP and ODP holes suitable for use by long-term recording that are located in areas of interest to the seismic community, and there appears to be little likelihood that many such holes will be drilled in the near future as the sites of interest in remote regions are of only minor interest to other disciplines. It isn't obvious that the drilling community would agree to spend precious ship time and resources to install holes for possible future use for science that might be done better by other means.

ENGINEERING CONSIDERATIONS IN LONG-TERM USE OF ODP BOREHOLES

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“Permanent” observatories are proposed on the ocean floor, making use of existing re-entry holes or drill holes yet to be established. Although there is a history of returning to and re-occupying a small number of re-entry holes up to fifteen years after they were established, no specific studies of the longevity of re-entry holes on the ocean floor have been made.

Before setting up "permanent" observatories on the ocean floor, it would be wise to study a number of existing DSDP/ODP boreholes with a view to answering a number of questions:

- How is the steel of the R/E core and casing corroding?
- Does the structure "settle" in some cases, i.e. sink a little into the seafloor? How much? Measurements of tilt in a ODP Hole 892B over a period of 10 months by Earl Davis suggest that some movement after emplacement does take place.
- What is the useful life of a R/E hole for a seismic observatory? Or for other types of observation?

The evidence from Hole 504B, which has been re-entered over 80 times over a period of 14 years since it was established, is encouraging. Other drill holes, established during the nineteen seventies while re-entry technology was still evolving, have been found to be filled with sediment. So we can already identify those re-entry holes which have been properly engineered. Nevertheless, it is important to obtain quantitative information about the stability and life span of re-entry holes.

BOREHOLE FLUID STUDIES

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Our laboratory has been involved in investigations of borehole fluids from DSDP/ODP holes long after these boreholes were abandoned. The principal objectives of the studies were:
(1) An investigation of the exchange of originally introduced surface waters with overlying bottom waters through convective mixing;
(2) An investigation of possible exchange of borehole fluids with formation waters from the surrounding rocks;
(3) An investigation of potential interactions between borehole fluids and the wall rocks of the surrounding formation.

For these studies use has been made of borehole re-entry exercises using either a drilling vessel (DSDP/ODP) or a wireline re-entry system, in particular the French NADIA (Navette Diagraphique) re-entry system (LeGrand et al., 1989; Gable and Scientific Party, 1992).

Drillship Re-entry

Three holes have been utilized for water sampling purposes:
Hole 395A - DSDP Leg 78A (McDuff, 1984)
Hole 418A - ODP Leg 102 (Gieskes et al., 1988)
Hole 504B -DSDP Legs 70, 83, 92, and ODP Legs 111, 137, and 140

Mottl and Gieskes (1990) have reviewed the information gathered between 1979 and 1988 (Legs 70-111). In that study the fluid exchange between the formation and the borehole fluids of Hole 504B could not be discounted. Subsequent studies, however, have indicated that in Hole 504B gradual replacement of borehole fluids by bottom waters does occur, in the upper part as a result of downward fluid flow and in the lower part as a result of convective exchange. In addition reactions involving interaction between borehole fluids and basaltic rubble accumulated in the bottom of the hole lead to a modification of the chemical composition of the fluids (Magenheim et al., 1992; in press).

Wireline Re-entry

For wireline re-entry two modes of re-entry have been developed: NADIA, as developed by Jaques LeGrand of IFREMER (LeGrand et al, 19989) and the Spiess Fly-in Re-entry system (Spiess and Boegeman, 1990).

Our efforts at obtaining *in situ* fluids samples have hitherto been directed towards two cruises involving NADIA: Operation FARE (Faisibilité de Ré-entree; LeGrand et al., 1989) and Operation DIANAUT (Gable and Scientific Party, 1992). During FARE we attempted to obtain one water sample in Hole 396A. Though this probe was the first tool to be used for re-entry, the tool malfunctioned. This did not discourage us and we proceeded to construct a multiple water sampler for DIANAUT. This device was deployed in Hole 395A and 534A (Gieskes and Magenheim, 12992). The results can be summarized as follows:

1. Hole 395A:
Data obtained in this hole suggest a complete flushing of the hole by bottom sea water, including the lower 150 m, showing evidence for convective mixing.

2. Hole 534A:
In this hole temperature observations in the upper part of the hole suggest upward fluid flow (Spiess and Boegeman, 1990; Gable et al., 1992). The chemical composition of the borehole fluids suggests inputs of fluids from an aquifer, located slightly below the location of the collapse of the hole (Gieskes and Magenheim, 1992).

The data gathered hitherto during the various re-entries have presented evidence that indeed various processes, as described in the objectives stated above, do contribute to observed changes in the borehole water chemical composition. In the future we aim to expand these studies to include visits to other re-entry holes as well as revisits to previously studied holes, using more sophisticated sampling equipment. Fore these purposes we are in the process of construction of a multiple water sampling device designed for the Spiess fly-in re-entry system. Prime targets are the seismic ODP Holes drilled off Hawaii, as well as revisits to Holes 395A, 296A, and 534A in the Atlantic Ocean. Especially Hole 534A is an excellent candidate for the monitoring of the borehole fluid chemistry as an indicator of inputs of the aquifer at about 725 mbsf. For these purposes continuous monitoring of temperatures in the upper part of the hole will be most illuminating, especially with regards to the postulated periodicity of aquifer fluids inputs.

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DOWNHOLE STRESS MEASUREMENTS

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The measurement of in situ stress plays both a critical and an ever-increasing role in enhancing our knowledge of the subsurface. Understanding the nature and origins of the contemporary in-situ stress field is fundamental to constraining models of local hydraulic fracturing, tectonic processes, and the driving mechanism of plate motion. Acoustic wave anisotropy, fracturing, and borehole breakouts are direct results of in-situ stresses, and can be used as indicators of local stress fields. The following summary of stress measurement techniques can be found in the published literature:

(1) anelastic strain recovery measurements on oriented core
(2) natural and coring induced fractures in oriented core
(3) overcoring of fractures induced by micro-fracture testing
(4) shear-wave birefringence and anisotropy measurements on oriented core

(5) borehole monitoring of fractures related to micro-seismic events and borehole breakouts
(6) borehole imaging of stress-induced and natural fractures

The first four techniques above all require oriented core. This can be done using either the scribe and survey method or a compass and camera survey tools, both of which perform measurements outside of the borehole environment. The last two techniques make measurements in-situ, but require significant structural information, such as the local rock strength or hydraulic fracturing pressure in order to estimate the in-situ stress field. Both measure the surficial formation properties around the borehole where stresses are highly concentrated, but usually these techniques indicate the maximum horizontal stress direction, not the stress magnitude.

Recent efforts in estimating stress magnitude and direction has focused on the use of orientated acoustic logging devices to measure in situ shear-wave splitting and velocity anisotropy. Both laboratory and borehole data have indicated that velocity and amplitude changes occur in anisotropic formations and have been qualitatively interpreted as the result of fracturing and stress effects. The advantage of this measurement approach is that compressional or shear waves may truly indicate in-situ stress effects away from near-field borehole disturbances. Provided that the wavelength of measurement is an order of magnitude larger than the radial borehole dimension, then the borehole has negligible effects on wave propagation, and shear-wave splitting and anisotropy can be directly related to fractures and far-field stresses. By re-entering existing ODP boreholes with azimuthal acoustic and other imaging tools, the relationship among borehole features, in-situ stresses, and acoustic wave propagation can be quantified over a broad geographic distribution in the oceans, greatly improving our knowledge of the nature and origin of stress in the crust.

Time-dependence of physical and borehole properties

Over time, as in situ stresses are applied to and fluids flow through the formations encountered by an ODP borehole, as well as the borehole itself, their physical properties change. Such temporal changes can only be measured by revisiting a borehole after a period of time has elapsed. Deploying acoustic televiewer or FMS imaging tools, azimuthal acoustic or standard logging tools, in ODP boreholes that were not loggable immediately after drilling, a unique data set consisting of both vertical and temporal changes in the physical and borehole properties can be acquired. Such 'time-stamped' profiles have only rarely been recorded in ODP -- just a few holes have been logged by re-entry or by revisits of the JOIDES Resolution (e.g. 418A and 504B). Revisiting other sites to acquire logs after drilling can provide new data on borehole shape, alteration mineralogy, physical properties, high-resolution detail of formation structures, and velocity anisotropy in holes where data have been previously acquired during or post- drilling. These data will address the evolution and structure of oceanic crust and sediments, changes in regional stress regimes, and the change in porosity and fluid movements over time.

TECHNOLOGY NEEDS TO STUDY REAL-TIME RIDGE CREST DEFORMATION AND SEISMICITY

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I am interested in conducting long-term observations on the seafloor, particularly in a ridge crest setting, and boreholes are an important component of such an effort. Within the context of the NSF RIDGE program I have been conducting a project to measure seafloor deformation (collaborators Spiess, Chadwell and Zumberge) and seafloor seismicity (collaborators Dorman, McClain and Webb) on the Juan de Fuca Ridge. In a ridge crest setting, crustal deformation and seismicity are linked with several others systems such as hydrothermal activity and biological eco-systems. The dynamic nature of the ridge crest, with rapid variations occurring on human time-scales, as well as on geologic time-scales, make it an ideal target for continuous monitoring.

Boreholes will play an important part of seafloor monitoring efforts because they provide a better coupling to the crust than is possible on surface positioned instruments. For some measurements the borehole provides the only window into the crustal process, such as for measurements of lithostatic/hydrostatic pressure. In other cases the borehole will give a superior coupling to the sea floor, such as for seismic sensors. Although deep boreholes have not yet been drilled on a ridge crest, even shallow (<100 m) boreholes would be useful for some long-term monitoring experiments.

To conduct long-term seafloor observations will require the development of new technology, for power, data storage/telemetry, improved sensors, environmental packaging, for placing equipment into boreholes, and for controlling the environment within the hole. I am interested in developing better technology for conducting these type of experiments, particularly using wireline re-entry rather than the drillship. The advantages of of wireline re-entry are reduced costs, and the potential for more frequent visits.

PHYSICAL PROPERTIES OF EARTH MATERIALS, SPECIFICALLY OCEANIC SEDIMENTS AND CRUST. WAVE PROPAGATION IN ANISOTROPIC MEDIA AND PHYSICAL MODELING.

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One application of ocean borehole and seafloor laboratories I would like to see is their use in cross-hole seismic tomographic studies. This would provide a high-resolution lateral variability image of physical properties, such as velocity and attenuation. With this information we could then estimate porosity, permeability, and anisotropic characteristics. Perhaps existing holes which are close in offset, such as 896 and 504B, could be used as a first attempt, followed by efforts to coordinate drilling future holes which would accommodate subsequent OBLISP use by including proper casing and enabling re-entry.

POST-DRILLING STUDIES TO DELINEATE OCEANIC MAGMATIC EMPLACEMENT AND ERUPTION

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I am interested in the general problem of magma flow from the mantle to the point of extrusion at spreading ridges. If we presume that the ocean crust in general consists of extrusive pillows and sheet flows, sheeted (or otherwise) dikes, and gabbros overlying mantle rocks, and that ridges have three dimensions (i.e., they are segmented), then there are several depth domains at which particular types of melt flow may be considered.

In the mantle

Geochemical data indicate that partial melting is accomplished by release or separation of small increments or fractions of melt from the source peridotites as they ascend diapirically beneath spreading ridges. However, the compositions of those melt increments are not those of eruptive basalts. Most of them must be greatly depleted in incompatible elements. At some point those incremental melts aggregate to form something like an average parental abyssal tholeiite having typical concentrations and ratios of incompatible elements. Drilling at Hess Deep shows that this aggregation occurs before melts leave the mantle and, indeed, that the base of the crust is fed by steeply dipping dikes ranging from centimeters to tens of centimeters in width.

Nonetheless, we do not know the three-dimensional geometry of these feeder systems (e.g., whether they are concentrated spatially beneath the centers of segments), nor whether melt supplied to the crust through them predominates over what might be termed seeps from a dispersed porous flow regime. The extent of magma pooling near the base of the crust is also uncertain.

In the gabbroic portion of the lower crust

Aggregated primitive magmas experience cooling and substantial crystallization in the gabbroic portion of the crust. However, this is no longer perceived as being within the confines of large axial magma chambers. Instead, drilling results support crystallization of most abyssal gabbros, at least those near the top of the gabbro section, in small (cm to meter-scale) dike-like bodies at both slow and fast-spreading ridges. Indeed, this has to be the case if geophysical studies are correct in limiting the region of detectable melt even at fast-spreading ridges to narrow and thin melt lenses at the base of the dikes. At slow-spreading ridges, the nearly entirely crystalline dike-like bodies of hot rock may be tectonically disrupted by deeply-penetrating listric normal faults, which enhance porosity, forming channels in a deformed crystalline matrix in which highly fractionated melts can concentrate and flow. At fast-spreading ridges, such faulting does not occur but the same general process of channelized flow of fractionated melts can be traced. The controlling structures are fracture or fissure networks which form in response to crustal dilation. The fissure swarms obviously open and close repeatedly, but highly fractionated magma eventually reaches the melt lenses at the bases of the dikes, where they can pond.

The same general questions about the geometry of the melt flow regime can thus be asked of the gabbroic portion of the crust as the peridotites. Are the processes frozen into the gabbros typical of the entire history of melt flow through the crust, or are eruptive episodes of heightened melt flow more important? Is channelized flow typical only of particular portions of ridge segments, or entire segments? Are there Kilauea-type central conduits beneath portions of segments?

In the upper crust

The principal questions here are 1) what is the role of neutral buoyancy in controlling the depth distribution and propagation mechanism of dikes? and 2) at fast-spreading ridges, does the melt lens itself feed dikes and eruptions? Tangentially, but of no less significance, is the question of the spatial and temporal relationship of hydrological systems, particularly vent fields, to the patterns of magma pooling (in melt lenses) and the eruption cycle.

What do we need to know?

We need to be able to *listen* to magma flow from the mantle to the lower crust, then through the lower crust (i.e., into melt lenses), then from the lower crust to the dikes, and finally at the eruptive stage. We need to be able to *target* the specific domains of melt flow as functions of depth and location along ridge segments, and *monitor* them for long periods of time (decades). We need to have instruments in place *at the eruptive stage*. Obviously, this is a seismological exercise. The MELT experiment is one designed to consider the upper mantle aspects of all of this, but obviously a short-term experiment will only provide some information. Most important, however, is that the types of melt flow that might be divined from frozen rocks, especially dike-like versus dispersed porous flow, might be distinguishable seismically, with the different types of flow characterizing particular portions of ridge segments, and/or particular intervals in their history. Fortunately, the shallow parts of the melt-flow regime appear to be much restricted geometrically to the immediate sub-axial region, thus need to be observed only at comparatively few stations. No large sound source is needed; these questions can be addressed mainly by monitoring local seismicity.

Apart from this, we need to measure the response of the crustal lid to melt flow (inflation-eruption cycles), to determine where melt if flowing, how fast it is moving, and how much of it there is. Tilt-meters, strain gauges, geodetic mapping, and so on, are the obvious techniques of choice.

Some of these instruments ought to be considered for emplacement in shallow drill holes. Surfaces of lava lakes may be good targets for installation of geodetic markers and tilt meters, and are easy places for guide-base activities. Other than that, offset-section drill holes in gabbros and shallow peridotites must be thoroughly investigated geophysically in order to understand the scales and geometries of the *record* of melt flow frozen into the rocks.

FLUID FLOW: HEAT AND MASS TRANSPORT

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My research interests are in fluid flow and associated heat and mass transport. I have worked extensively on modeling of thermohaline convection around salt structures, basin scale flow by topographically-driven recharge, and pressure-driven flow along faults. I am especially interested in the dynamic relationship between stress, pore pressure and permeability of faults and geopressured sediments. In November and December of 1993, the Global Basins Research Network with funding from the U.S. Department of Energy and in cooperation with Pennzoil drilled into a series of growth faults in the pressure transition zone in the Eugene Island Area, Offshore Louisiana. Our results are similar to ODP studies of decollement zones in accretionary wedges. Pore Pressures are very high (> 90% of lithostatic pressure) and fault zone permeability is highly dependent on pore pressure. My modeling results of this region also indicates that duration and periodicity of fluid expulsion along faults is dependent on the permeability of surrounding sediments (e.g., their ability to provide or absorb fluid to or from the fault zone). Thus, the presence of a permeable sand layer below the top of geopressure extends the duration of an expulsion event by an order of magnitude (from decades to centuries) by focusing fluid from a broad region into the fault zone. I would be interested in the following types of OBLISP experiments:

Stress, Pore Pressure and Fault Permeability 1: After drilling into a fault zone (either accretionary wedge decollement or growth fault through the top of geopressure), conduct a series of packer tests. This would include both pressure draw downs as well as pumping fluid into the fault zone. Because permeability is highly sensitive to pore pressure it makes more sense to pump water into the fault zone. Our results in Eugene Island indicate that fault permeabilities are on the order of a Darcy for pumping fluid into the fault zone. This would make it possible to pump fluid towards another well in a reasonable amount of time in a dual well experiment. It may also be possible to observe changes in the fault zone from associated seismic studies (cross borehole tomography or a seismic network on the sea floor). If we can jack open a fracture network in the fault zone, we might be able to produce an observable bright spot or microseismicity. Finally, it might be possible to determine the location and permeability of fault zones by pumping in water of a different salinity and observing differences in resistivity logs run before and after pumping. This technique has been successfully used on land.

Stress, Pore Pressure and Fault Permeability 2: Drill into a permeable layer either above (geopressured zone) or below (decollement) a fault zone with pore pressure dependent permeability. Then conduct a series of packer experiments to see if we can induce flow along the fault without collapsing the fracture network by drawing down pressure in the adjacent permeable layer. Drilling in Eugene Island suggests that oil production in reservoir sands has induced flow up the growth faults (e.g., the Eugene Island field has produced more than 100% of estimated reserves as opposed to typical values of 25 to 40%). However, our attempts to produce fluids directly from the fault zone were unsuccessful because the harder we pumped the lower the permeability of the formation became. It would be of enormous interest to oil companies if we can show how fluids migrate along pore pressure sensitive faults.

Stress, Pore Pressure and Fault Permeability 3: In a tectonically active region, such as a subduction zone, conduct long term monitoring of pore pressure, temperature and stress. Presently, it is unclear what the duration and periodicity of fluid expulsion events might be. Are fluid expulsion events short lived and frequent with effective stress rapidly oscillating around some critical value for maintaining an open fracture network or are fluid expulsion events long lived and infrequent with corresponding large oscillations in effective stress. My modeling studies indicate that pore pressure rapidly rebuilds after fluid expulsion to just below a critical value for opening fractures. It then takes a long time for pore pressure to build up above that critical value and induce a new expulsion event if the stress field is constant. This implies that relatively small changes in the external stress fluid might be able to initiate a fluid expulsion event.

Heat Flow on Crests/Flanks: Long term temperature/heat flow measurements to document the spatial and temporal scales of convective heat transport. It is very unclear to me how shallow free convection can provide high heat flow for tens of millions of years. Either convection must vary spatially or temporally or it must be layered so that deep heat is tapped and efficiently transported to the surface. Conduction cannot keep pace. As far as I am away, there is only a single study by Chapman and others which has attempted to measure the spatial scale of free convection in the ocean floor.

LONG-TERM SUB-SEAFLOOR OBSERVATIONS AND INVESTIGATIONS

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I would classify my interests in sub-seafloor observations into two distinct groups. The first is the science that I am interested in, and the second is a more technological and operational approach that I think needs to be considered up-front.

1. Science Interests:

I have been involved in research on the fluid and structural evolution of active margins, and there are a number of sub-seafloor investigations that I would like to see go forward. First of all, all of our direct observations (submersible, ROV), have shown that the processes that control fluid flow are transient in both space and time. On the seafloor we utilize biology (chemoautotrophic organisms) and chemical precipitates (authigenic carbonate) to indicate present and past fluid flow, respectively. Where we find "cold seep" organisms we know that sulfide- or methane-rich fluids are presently being expelled, and where we find carbonate we know that methane-rich fluids were venting in the past. Ocean drilling has expanded our knowledge of fluid evolution and structural fabrics into the third dimension, and has retrieved valuable fluid samples and core. Recently, we have begun to CORK these holes for longer-term fluid and thermal investigations. The present generation of CORKs collects pore pressure and thermistor data, and there are plans to add in situ chemical analyses to these (using osmo-analyzers). Post-cruise analysis of Cascadia Leg 146 cores convincingly shows that porosity, permeability, and pore pressure are all affected by strain and strain rate, which leads to the question of static versus dynamic fluid and physical properties. The next generation of CORKed holes should collect data on pore pressure and heat flow, but should also be instrumented to look at long term changes in physical properties. Due to hole instability most drilling in accretionary complexes needs to utilize casings, but downhole instruments exist that can assess physical properties, such as porosity, through the casing.

Another question concerns the relationship of fluid and physical properties to seismicity. Recent drilling off Barbados on Leg 156 suggests that polarity reversals observed on MCS data are the result of dynamically maintained zones of high pore pressure, and that the fluid within these zones may be far-traveled. The question remains as to how these "packages" of fluid move over time, and what the affects of changing physical properties are. One suggestion is that during regional seismic events short term loading creates localized overpressuring, leading to fracturing and toe-ward migration of the fluid and the fracture. Between seismic events the fluid may move more slowly, utilizing the anisotropic permeability inherent to the fault zone that would be orders of magnitude less than the seismically induced permeability. The only way to test this hypothesis is to seal a hole in a seismically active region and monitor the fluid and physical properties over time; a possible candidate would be the Costa Rica accretionary complex.

In accretionary complexes the décollement acts as a major fluid conduit and structural barrier. Above the décollement the maximum compressive stress is more or less horizontal, whereas below the décollement sigma one is closer to vertical. Fluids below the décollement migrate toward the toe, with little leakage to the over-riding section. Because of this, it is imperative that there be separate sealed sections above and below the décollement. This could be done by sealing multiple sections in one hole, or by drilling several holes and packing off different sections. It would be valuable to measure strain in these instrumented boreholes as well. This could be done by means of a tiltmeter, or by examining the shape changes of the casing over time. The toe, which is a region of likely aseismic slip, is the region that is completely pierced by drilling, and these drill holes provide an attractive laboratory for studying strain in the overriding section as well as on the décollement.

2. Operational Considerations:

Much of the discussion at the December, 1994 OBLISP meeting focussed on instrument packages that would be either lowered down into boreholes or would reside on top of a CORK-like platform. All of the instruments and experiments will have common needs of data logging, data storage, available power, and post-experiment data interrogation. Many people may feel that these are just engineering problems, and therefore are not central to our objectives, but I suggest that they are in fact the bottleneck that will hold back the long term success of sub-seafloor observations.

a) Power Capacity. All untethered science on the seafloor is limited by the quantity of available power. This will be particularly true for long term sub-seafloor investigations. As a community, we need to improve, by several orders of magnitude, the amount of power available over the long run. These batteries will need to be dependable over a period of years or more. We also need to make battery swaps underwater routine by defining an operational standard of quick connects and disconnects. Underwater battery swaps should be feasible with both ROVs and submersibles. By ensuring continuous power over a period of years to decades we open the door for true long term observatories. This problem is not unique to borehole investigations, but it is critical to our success.

b) Data Logging. Exceptional experiments fail when the data fail to be logged. We need to define a standard data logging configuration that includes self back-ups, and pursue a truly dependable system. Once a standard is established it can be used for most, if not all, experiment packages, making transportability an option from one experiment to another.

c) Data Storage. As the number of sub-seafloor experiments increases the amount of data produced will snowball. These observatories will need large and dependable data storage systems. Sub-seafloor experiments should not be data storage space limited.

d) Data Interrogation and Instrument Servicing. Currently we use submersibles or wireline re-entry vehicles to retrieve data and samples from CORKed boreholes. However, the technology exists to use the water column as an acoustic modem. I would like to see us, as a community, utilize surface ships (perhaps on a target-of-opportunity basis) to collect much of the data from sub-seafloor observatories. At that point we could determine the health of the instrument package and the amount of remaining battery power. If low power were detected, and the instrument still functioning up to specification, then we could muster deep submergence assets for battery servicing. Deep sea assets, due to their high costs, should be the platform of last resort for borehole interrogation.

TOWARDS A PERMANENT NETWORK OF OCEAN FLOOR SEISMOLOGICAL OBSERVATORIES

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During the past decade the global seismological community has made considerable progress towards the construction of an effective network of high-quality digital broad-band seismological observatories to monitor the earth's natural earthquake activity. The US IRIS program anticipates that within the next few years it will achieve its original goal of contributing one hundred new stations to the global coverage. Already the data that these new broad-band stations are producing are having a profound impact upon our knowledge of deep- earth structure and the active processes that generate our planet's seismic activity. Nevertheless the station distribution within the new network is flawed because of its inadequate coverage of the oceans. This problem has been recognized for a number of years and several engineering efforts within the US, France and Japan are underway to devise solutions.

At a workshop in Woods Hole Ma. in April 1988, supported by JOI/USSAC, the outline of a plan for a network of ocean floor seismic stations was established (Purdy and Dziewonski, 1988). This plan called for approximately 15-20 stations distributed within the worlds oceans as shown on the attached figure. This workshop also identified the key technical challenges associated with the realization of this plan. Profound difficulties are anticipated with the installation of broad band sensors on the ocean floor in order to minimize background noise and insure high fidelity recording of (especially horizontal) ground motion. The need for several watts of continuous power to operate 24 bit A-to-D systems and modern broad band sensors, combined with the requirement to record or retrieve approximately 20 megabytes of data per day, constitute significant technical and engineering challenges. It is clear that construction of the permanent network (dubbed OSN for Ocean Seismic Network) should not begin until satisfactory progress has been made towards the solution of these problems. Experiments by Japanese (Suyehiro et al 1992) and French (Montagner et al 1994a,b) colleagues have already proved that the fundamental goal of recording useful broad band data on the deep-ocean floor is realizable, but have left unresolved the key issue of whether it is essential to install sensors down boreholes into basaltic basement.

Existing plans within the US for progress with OSN call for a three phase approach. In Phase 1 pilot experiments are proposed to address the fundamental physical problems of sensor coupling and noise, and devise solutions to the technical issues of power, data retrieval and system reliability on the multiple year time scale. In Phase 2 a small number of prototype observatories are installed that immediately begin contributing data to the seismological community, but which also, through the collection of auxiliary data sets (e.g. currents, wind speeds, seafloor seismic sensors) and through their contrasting locations (varying sediment thicknesses, proximity to coastlines) provide new understanding of the optimal design and siting of ocean floor seismic observatories. In Phase 3 the complete network of 15-20 stations is installed and efficient schemes for the long-term support and maintenance of the instrumentation are devised. This is conceived at all stages to be an international effort, with each country contributing independently their knowledge and expertise to each Phase.

One of the most important 'spin-offs' from this development of the capability to build a permanent observatory will be the knowledge of how to build portable instruments to record broad band seismic data on the ocean floor, and the compromises in data quality and noise levels (if any) associated with such systems. There are many exciting problems related to ocean lithosphere structure and to the properties of the upper mantle beneath mid-ocean ridges, for example, that are best addressed by arrays of portable instruments. As has been proven the case on the continents, the roles of permanent and portable broad-band instrumentation are complementary and each contribute uniquely to our understanding of earth structure and processes.

Within the US funding is in place to design and construct two separate ocean floor broad band systems. The first is a downhole system, being developed under NSF sponsorship jointly by Scripps and Wood Hole. It utilizes a Teledyne- Geotech 54000 sensor and is designed to be installed by a conventional research vessel within ODP boreholes in the deep ocean using the USSAC-supported wireline control vehicle designed and operated by Fred Spiess at Scripps. The second is a Broad-Band Ocean Bottom Seismometer (B-BOBS) that uses a standard Guralp CMG3-T sensor mounted in an external package that can either be emplaced upon, or surficially buried beneath, the ocean floor. This is a co-operative project between Scripps, Woods Hole and the University of Miami, with Miami taking the lead in the design of the wireline system that carries out the burial of the sensor package. Funding is in hand from NSF and IRIS for construction of two B-BOBS.

Detailed plans exist to carry out an extensive set of Pilot Experiments using these instruments beginning in October 1996 at ODP Site 843 located south of Oahu (Dziewonski, Wilkens et al., 1992). This drill hole (OSN-1) was located and drilled specifically as a site for experiments in the development of broad- band instrumentation. The experiments to be carried out in 1996 are described in detail by Forsyth et al., 1991. They consist of a three-month-long continuous recording of broad-band data from co-located downhole, seafloor and surficially buried sensors and the comparison of these results with those from a nearby GSN island station (in this case the Kipapa Tunnel on Oahu).

The research objectives attainable using data from an ocean seismic network have been well described elsewhere in this report. Sufficient progress has been made with engineering developments in the US, France and Japan in recent years that it is clear that OSN technically is a practical objective. Nevertheless, progress towards the OSN objectives within the US has been tortuously slow. One important reason for this is that there exists no program to support the development of new bore hole instrumentation and encourage the wider use of ODP sites as natural observatories from which to monitor the earth's active processes. It is hoped that the OBLISP program described in this report will fill this important void.

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WIRELINE REENTRY

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My interest is in ocean technology and the fine scale nature of the sea floor. In addition to our Deep Tow multifunction survey system and seafloor geodetic activities, this has led to development of technological and operational capabilities for placing equipment in drill holes, without need for a drilling ship or a manned submersible. The present system can place equipment (e.g. seismometers and recording packages) in holes in the deep sea, and includes a simple logging tool (temperature, pressure, tilt, cross section shape), and development of a water sampler to work with the tool.

The central part of the system is the Control Vehicle which can be maneuvered locally on the end of a standard 0.68" electromechanical cable, with a payload (e.g. logging tool, seismometers) suspended below it. TV, lights, sonar, and long baseline acoustic navigation are used to determine the location of the hole and to maneuver the CV to place the load in the hole. This can include use of a soft electrical connecting tether between the CV and the payload to provide power, control signals and uplink data transmission without the motion of the CV disturbing the load in the hole.

Up to 300 kHz of bandwidth and 10 kVA of single phase power can be available for payload use. Voltage outputs (110 or 220 V AC, or various DC supplies) can be provided from the Control Vehicle. Maximum payload in-water weight is determined by the capability of the wire and the amount of wire needed to reach the desired instrument depth below the sea surface. In the 1989 reentry operation the payload was about 1,000 lbs and the water depth was 5,000 m.

The logging tool includes slow scan TV, lights, hydrophone, Paroscientific pressure gauge, tilt sensors, platinum resistance thermometer, and either a three arm caliper or a 24 beam acoustic caliper. Tool electronics are good to 100^o C, but some redesign would be required to reach significantly higher temperatures. The water sampler under development with Gieskes is to acquire 3 uncontaminated 1 liter samples, each independently triggered from the surface.

Topside equipment includes readouts, displays, and recording devices for Control Vehicle operation and logging tool data, and up and down link multiplexing for operation on the 0.68" coax, as well as high voltage supply (2400 V). The system can be operated from any ship capable of handling 0.68" wire. Best results require a ship with dynamic positioning (e.g. Knorr, Melville, Thompson, Revelle).

Limited funds are available for preliminary technical and operational consulting with potential users. Contacts for further information: John Hildebrand or Fred Spiess.

POROSITY AND SCALE ISSUES IN SEAFLOOR STRUCTURE

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Two common and recurrent themes continually emerge in the discussion of both sediment and igneous structure of the seafloor: porosity and scale. Porosity and the related topic of aspect ratio spectra tend to dominate seismic velocity changes rather than petrology. Scale issues arise when correlating well log and sample results with either seismic refraction results (for igneous properties) or seismic reflection results (for sedimentary sequences). These statements are obviously simplifications but they probably cover about 90% of the work done on seafloor physical properties. Although they apply principally to seismic properties they hold reasonably well for magnetic, electrical, and heat flow properties as well.

Structure is essential in unravelling issues of crustal emplacement and evolution, sedimentary basin and continental margin evolution, and both hydrothermal and chemical processes in the crust and sediments. By focusing on the key issues of porosity (and aspect ratio) and scale, long term borehole observatories on the seafloor can provide the necessary structural information to constrain hypotheses of the broader scientific processes.

As an example my favorite project is borehole seismology. In some situations such as VSP's or offset VSP's the borehole seismic geometry provides a unique look at a particular scale of structural heterogeneity (100-1km) and porosity (10cm-10m) and can be used to measure the orientation of large scale cracks and fissures that are responsible for seismic anisotropy in the seafloor. However borehole seismometers have the additional potential of providing good quality seismic observations in the ULF (1000s-1Hz) and VLF (1Hz-100Hz) bands. The advantages of borehole seismometers as seismic sensors are being addressed as part of the Ocean Seismic Network program.

There are many examples in the literature of VSP's and offset VSP's being applied to address intermediate scale porosity issues. These are evident even in normal incidence VSP's but the offset VSP's give additional information on lateral heterogeneity and anisotropy. In igneous environments particularly, heterogeneity and anisotropy are difficult to observe at either the larger refraction scale or smaller logging and hand sample scale.

I would propose that a borehole seismic program be carried out with the WHOI SEABASS four sonde borehole seismic system. A well coupled borehole sensor at about 500m depth would give good coverage of the lateral heterogeneity and anisotropy in the upper crust and in sedimentary sequences out to ranges of 8km. The experiment would be useful at 395 or 396 at the mid-Atlantic Ridge, other shallow ridge boreholes and the upcoming holes to be drilled in the clathrates on the Carolina Rise and Blake Ridge. The same borehole array could be used to carry out VSP's with innovative sources such as a seafloor shear wave sources, high frequency (1Khz-10Khz) sensors, or deep towed flextensional sources. The array would also acquire useful ambient noise data in the band 2-100Hz as a function of depth in the seafloor to meet OSN objectives. The same array could be used in crosswell tomography experiments in areas where two holes exist within about 1km of each other (eg. 504B and 896A).

PLANNED USE OF DRILL HOLES FOR SCIENTIFIC EXPERIMENTATION AND OBSERVATION OF HYDROTHERMAL SYSTEMS AT SEDIMENT-COVERED SPREADING CENTERS

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The proposal for a second leg of ODP drilling to address hydrothermal circulation and massive sulfide mineralization at the Middle Valley and Escanaba Trough sedimented ridges (SR II) has been included on the FY 1996 drilling schedule. This drilling provides an excellent opportunity to extend the function of the drill ship beyond observation to active experimentation. Drilling in the active hydrothermal field in Middle Valley on Leg 139 (SR I) demonstrated that drilling-induced disturbances could provide important information on properties controlling hydrothermal circulation, including pore pressure and permeability. The first deployments of the CORK borehole seals occurred during Leg 139 (Davis et al., 1992). Two re-entry holes (857D and 858G) were instrumented with pressure transducers and string of thermistors to monitor the recovery of the drill holes from the thermal disturbance induced by circulation of surface seawater during drilling. The instrument recording packages have either been damaged (857D) or failed due to high temperature (858G) and hydrothermal fluid is presently venting from Hole 858G. The initial records from these simple seafloor observatories provide important constraints on the physical properties of the upper oceanic crust and overlying sediment, including the thermal structure, in-situ pore-pressure, and formation scale permeability (Davis and Becker, 1994). Pre- and post-drilling monitoring and sampling in the active hydrothermal fields targeted for drilling during SR II will further document hydrologic, geochemical, and biological changes induced by drilling, allowing new insights on processes controlling hydrothermal circulation.

The drilling plan calls for replacement of the instrument strings and data recording packages in both of the CORKed holes. Removal of the present bore hole seals will allow temperature logging and fluid sampling in these thermally equilibrated drill holes prior to introduction of cold surface seawater, which is circulated during drilling. An effort will be made to minimize disturbance of Hole 858G, located in the center of the Dead Dog vent field, during re-instrumentation and re-CORKing. Hole 857D, located 1.6 km to the south, will be deepened, logged, and subjected to packer tests prior to re-CORKing. Measurements from the existing CORKs indicate that introduction of cold seawater into the hot formation at Hole 857D will lead to an approximately 1 MPa overpressure relative to in situ pore pressure. This pressure change is comparable to the change caused by deep man-made lakes which are known to induce earthquakes. If we assume that the rocks near the ridge axis are in a tensional state near failure by normal faulting, then the increased pore pressure should induce localized failure detectable by OBS. This presents a fascinating opportunity to investigate the geometry and mechanism of faulting in a hydrothermally active ridge environment. Therefore, an OBS array should be deployed prior to drilling to assess natural seismicity and should continue recording during and after drilling to monitor drilling induced seismicity.

The large pressure transient induced during drilling will also provide the opportunity for a hole-to-hole hydrologic experiment to assess the lateral permeability at the km-scale. Calculations based on measured pore pressure and permeability in the two CORKed holes indicate the over pressure induced by introduction of cold seawater into Hole 857D during drilling should be observable as perturbation that can be monitored in Hole 858G. Prior to sealing Hole 857D with a CORK on Leg 139, the formation was accepting surface sea water at a rate in excess of 10,000 l/min (Davis et al., 1992). This flow will be restimulated for the few day interval when Hole 857D is unCORKed prior to deepening and logging. This hole will then be reCORKed ending a brief transient pressure pulse that should be of sufficient amplitude to be observable in the pressures recorded at the reCORKed Hole 858G 1.6 km away. If successful, the results of this experiment would provide the first determination of the lateral permeability in a seafloor hydrothermal system at the scale of a hydrothermal convection cell. It is intended to equip the CORK in Hole 858G with an acoustic data link so that the pressure field within this hole can be monitored in real time to determine the optimum timing of other drilling in the area. At some point in the future, Hole 858G will be unCORKed for use as a point source vent that is cased directly to basement bypassing the flow path through the sediment section taken by natural vent fluids. This point source vent located in a re-enterable hole is likely to become a seafloor laboratory accessible to experimentation by submersible or ROV.

Drilling is also planned for the hydrothermal system in Escanaba Trough on the southern Gorda Ridge and at least one re-enterable hole is intended to penetrate into igneous basement rocks. The present drilling plan does not call for instrumenting this hole due to the high cost, both in terms of drill time and ODP operational funds, necessary to install a CORK. Regardless of whether this hole is left open or sealed, it represents a hydrologic experiment and a potential perturbation of the hydrothermal field. It also presents another seafloor laboratory accessible to experimentation by submersible or ROV.

A further area for consideration is the use of drill holes for biological experimentation. Recent observations of the ejection of large quantities of microbe-rich particulates following dike injection events raises the question of the extent of subsurface microbial production. The depth of a subsurface biosphere remains to be determined. A systematic study of the vertical extent of subseafloor growth will likely require some tool and procedural development. Sedimented Ridges II drilling will provide an opportunity to develop and test a sampling protocol in advance of a leg dedicated to investigation of the base of the biosphere. Additionally, the retrieval of the thermistor strings and sampling tubes from the two CORKed holes in Middle Valley presents a unique opportunity to sample any thermophilic bacteria that might have colonized these surfaces because the temperature and pressure conditions have been measured and the ambient fluid will be directly sampled.

There is an opportunity to establish a sedimented ridges biological observatory at Middle Valley, in the active vent field. The CORKs at Holes 858G and 857D, when refitted with new thermistor strings, pressure transducers, and acoustic modems, will permit long-term monitoring of hydrothermal fluid supply to the vent field. Coupled with periodic re-mapping of organism distribution and heat flow, this monitoring system is a potentially powerful tool for studying the influence of variability in hydrothermal activity on vent communities. The proposed two-hole experiment involving Holes 857D and 858G effectively represents the controlled manipulation of an entire hydrothermal system. This offers an excellent opportunity to study the effects of sub-surface hydrological variations on fluid supply to vent communities such as bivalve beds, and the consequences for vent organisms, including behavioral and biochemical responses.

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MEASURING REGIONAL HYDRAULIC PROPERTIES OF OCEAN CRUST

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Although crustal hydraulic properties have been determined with various types of instrumentation deployed in DSDP/ODP holes, they have typically provided information useful for these properties localized to the vicinity (i.e., within a few diameters) of the drill holes. Regional properties in the vicinity of boreholes may also be obtained from either cross-borehole experiments, or from longer-term recording instruments that can be placed on or below the nearby seafloor. This is to outline the concept of some experiments that may help to determine the fluid permeability and transmissivity of upper ocean crust at a regional scale of several km, parameters that are difficult to obtain at this scale from conventional borehole experiments but that are important to constrain models of fluid flow and even formation of the crust.

Downhole experiments in individual boreholes that penetrate young ocean crust have already provided useful data to design an experiment. Packer experiments give a relatively high value for upper crustal (few tens to perhaps 200 m depth below sediment/rock interface) fluid permeability, of order 10^{-12} to 10^{-13} m^2. The fluid permeability of the deeper crust below decreases to order 10^{-17} to 10^{-18} m^2, which effectively inhibits any significant hydrothermal circulation. Any sediment cover above also has a relatively low fluid permeability, of order 10^{-16} to 10^{-17} m^2 for marine pelagic sediments. Hence the physical situation is a relatively thin high permeability layer sandwiched between the relatively low permeability sediments above and deeper crust below. Boreholes that have penetrated into the upper crust below a relatively uniform sediment cover usually exhibit downflow in the hole and/or sub-hydrostatic pressures in the upper basement rocks. The initial downflow rates can be quite rapid on young crust, of order several thousand L/hr or more at sites 504 and 395. Vertical pore pressure gradients are of order 10 to 25% sub-hydrostatic, as determined by shutting in the flow by hydraulic packers.

Numerical modeling of this physical situation, with heat flux from below, shows that these pore pressure gradients and related fluid flows (mostly in the high permeability upper crustal layer) can be realistically simulated. The corresponding lateral heat flux variability measured along the seafloor can also be simulated in these models. It seems that most of the fluid flow takes place in the high permeability upper crustal layer with large aspect ratios for the geometry of the circulation cells. The hydrothermal flow takes place at sub-critical Rayleigh numbers, and may continue until the permeability becomes significantly lower as a result of rock alteration.

An experiment to determine the regional hydraulic properties is based on the transient pressure field created when a borehole is drilled into the permeable crustal layer. A nearly hydrostatic pressure gradient will be superimposed on the pre-existing anomalous pressure field at the borehole, which will diffuse primarily into the permeable layer around the borehole at a rate that depends primarily on its hydraulic properties. For a permeability of 10^{-13} m^2, the hydraulic diffusivity of the layer, given as $D=k/PMC$ (where k is permeability, P is porosity, M is fluid viscosity, and C is fluid compressibility), is about 0.2 m^2/s, about 6 orders of magnitude greater than the thermal diffusivity of the layer. This will allow the pressure field to diffuse outward from the borehole to distances of order 1 to 4 km over times of 1 to 12 months, respectively.

Over this time, the vertical pressure gradients in the sediment layer above will also change in response to this altered basal boundary condition, which can be measured by pore pressure instruments which can be deployed as a function of distance from the borehole. The hydraulic diffusivity of sediments is also about 2 orders of magnitude larger than their thermal diffusivity, such that we may expect to see a pressure gradient change at the seafloor within less than 1 year after a pressure change at the base of sediments with thicknesses less than a few tens of m. For greater sediment thickness (>100 m), times will be of order 10 years or more, such that such seafloor experiments are probably feasible only on relatively young crust with a relatively uninterrupted sediment cover of order a few tens of m.

Autonomous long-term recording pore pressure instrumentation either now exists or is under active development to carry out such measurements, so that new technical developments are not required. The main requirement is to establish a borehole and deploy instrumentation at an appropriate location.