Workshop on Linkages Between the ***Ocean Observatories Initiative*** and the ***Integrated Ocean Drilling Program***

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Preface and Acknowledgements

This report comprises a summary of discussion and recommendations from a workshop designed to codify and develop linkages between the Integrated Ocean Drilling Program (IODP) and the Ocean Observatories Initiative (OOI). The need for this workshop became clear from conversations among individuals involved in one or both programs over the preceding year, based on the recognition of the many ways in which coordination between the IODP and the OOI could help to move both initiatives forward, develop new tools and techniques, excite scientific and public communities, and create unprecedented opportunities for profound, rapid progress to resolve outstanding questions in Earth, Ocean, and Biological Science and related disciplines.

Sixty-five researchers, educators, and administrators gathered for two days in the Applied Physics Laboratory (APL) at the University of Washington, Seattle, WA, to review the organization and status of the IODP and the OOI, elucidate common thematic goals and technical needs, and prepare a set of focused recommendations. Workshop participants included individuals from around the U.S. and around the world who have a wide range of experience. The discussions were energetic, free-ranging, inspiring, and often surprising.

This workshop could not have been held without the financial support of the U.S. Science Support Program for the Ocean Drilling Program, administered by the Joint Oceanographic Institutions, Inc. (Contract #JSC 3-04), which provided funds for planning, advertisement, travel, and related costs. The Neptune Office, University of Washington, provided administrative, design, and web-hosting support, coordinated use of APL facilities, and covered costs for food and drinks at the workshop. We particularly appreciated the talent, dedication, and good humor of Liesje Bertoldi, Conference Coordinator, who kept track of applications and funding allocations, made sure that there were working data projectors in all of the rooms, collected text and figures from the thematic and technical groups, kept a running record of workshop activities, and otherwise made sure that dozens of necessary tasks were completed before, during, and after the event. Finally, the workshop participants gratefully acknowledge our colleagues at the National Science Foundation, without whose vision and determination we would only dream of the exciting discoveries that are sure to come.

I. Executive Summary

A workshop was held in Seattle, WA during June 2003 to discuss linkages between the Ocean Observatories Initiative (OOI) and the Integrated Ocean Drilling Program (IODP), including common interests related to scientific, technical, educational, and administrative goals. The IODP has just begun operations, and the OOI will soon become part of Ocean Research Interactive Observatory Networks (ORION), a long-term effort to develop, emplace, and maintain oceanic observatories in several settings.

The IODP and OOI share many common goals and challenges including: needs for infrastructure investment and commitment by numerous scientists, engineers, and educators; operation through a combination of top-down, long-term planning and grass-roots scientific proposals; unprecedented opportunities for education and outreach to both scientific and nonscientific audiences; an emphasis on "active processes" within the global ocean; a sustained commitment to technological development, including design, prototyping, and testing; and a dependence of each program on the successes of the other.

The primary aim of the workshop was to provide the scientific rationale that will underpin a broad range of scientific, technical, and educational programs involving ocean drilling and observatories. The specific goals of the workshop were to:

(1) Articulate and codify common goals of the IODP and OOI, in preparation for a community-wide OOI meeting planned for early 2004;

(2) Identify experiments and technology necessary to achieve critical, common objectives;

(3) Establish dialog between scientists, technologists, and educators interested in one or both programs; and

(4) Encourage involvement by people who have not previously participated in planning or scientific activities for the IODP or OOI

Workshop participants were split into thematic and technical groups, and also met as a whole to discuss broad recommendations regarding the development of both programs. Discussions and recommendations are described in greater detail in the rest of this report, and discussed in the context of particular experiments in Appendix X, but specific recommendations are summarized as follows (please also see Section VII. Recommendations and Conclusions for more explanation):

Recommendation #1: Take advantage of common opportunities through the IODP and OOI (ORION) to exploit efficiencies of scale and multidisciplinary approaches.

Recommendation #2: Internationalize ORION to entrain the broadest possible community of scientists and educators.

Recommendation #3: Develop fully-integrated education and outreach programs, which should be considered to be long-term investments with many benefits.

Recommendation #4: Coordinate access to boreholes and other facilities to avoid conflict and maximize multidisciplinary opportunities.

Recommendation #5: Recognize and plan for asset (platform, survey) needs, for site survey, observatory emplacement, maintenance, and repair.

Recommendation #6: Accelerate development of essential sensors, samplers, and related technology that will be required by both programs.

Recommendation #7: Continue development of improved drilling, casing, and completion technologies.

Recommendation #8: Reconsider the nature of “event response” so as to maximize the long-term presence within dynamic systems.

Recommendation #9: Integrate use of models, site surveys, and subseafloor observatories to develop and test hypotheses.

Recommendation #10: Support training of a new generation of scientists, engineers, and educators.

Recommendation #11: Don’t be afraid to think big, or to make incremental progress; let long-term goals drive both programs, but work on manageable pieces as opportunities allow.

II. Introduction and Workshop Goals

A. Existing and Planned Programs

Plans have developed rapidly over the last several years for establishment of the Integrated Ocean Drilling Program (IODP) as the successor to the current phase of scientific ocean drilling, the Ocean Drilling Program (ODP). ODP at-sea operations ended in 2003, and

IODP is planning to begin operations in 2004. A series of community meetings and workshops held over the last six years, and reports generated by participants in these efforts [e.g., *COMPLEX*, 2000; *COMPOST*, 1993; *COMPOST II*, 1998; *CONCORD*, 1997; *FUMAGES*, 1997], described the essential roles that scientific ocean drilling has played in advancing Earth Science and related fields during the last 30 years, and helped to identify critical scientific and technical goals for the new program and the means by which these goals should be achieved. This approach of bringing together an interdisciplinary group of motivated individuals to discuss and codify scientific, technical, and administrative needs during a brief workshop, followed by preparation of a highly focused document that can be used by a broader community in planning and designing exciting scientific programs, has proven to be enormously successful. The process is relatively inexpensive, efficient, transparent, and driven by grass-roots initiative.

One notable category of technical and scientific success during ODP, frequently cited in workshop reports and planning documents, was establishment of long-term sub-seafloor observatories for monitoring of conditions surrounding a borehole following a period of equilibration after drilling [*Becker and Davis*, 2000; *Davis and Becker*, 2002a; *Davis and Becker*, 2002b; *Davis et al.*, 1992]. To date, 18 long-term, sealed-borehole observatory systems (CORKs) have been deployed in settings ranging from ridge-crest to mid-plate to active margin. Data and samples acquired by these systems have helped to document remarkable processes occurring within the seafloor, including transient fluid flow events, pressure responses to seismic events tens of kilometers from the observatory site, and the existence of unusual microfauna within remote crustal reservoirs [e.g., *Cowen et al.*, 2003; *Davis et al.*, 1993; *Davis et al.*, 2001]. An additional nine reentry holes have hosted, or are intended to host, short-term or long-term seismometers [e.g., *ION*, 2001; *Montagner and Lancelot*, 1995; *Stephen et al.*, 2003; *Suyehiro*, 2002] to investigate both deep Earth and seismogenic processes associated with subduction.

Plans for development of a series of long-term observatories on the seafloor are moving forward under U.S. and international leadership [*Detrick et al.*, 2003]. Within the U.S., the Ocean Observatories Initiative (OOI) is expected to develop three principal elements: (a) a cabled regional observatory, (b) relocatable deep-sea observatories, (c) and a network of coastal observatories. Various components of these systems are being developed or deployed around the world, and there have been a series of meetings and workshops that, like their ODP and IODP counterparts, are intended to help plan for cooperative scientific and technical developments [e.g., *Detrick et al.*, 2003; *Frosch*, 1999; *Glenn and Dickey*, 2003; *NRC*, 2000]. Additional meetings are planned for late 2003 and early 2004, including an international, community-wide meeting to be held in January 2004 in Puerto Rico (ORION). By design, earlier observatory workshops have emphasized breadth rather than depth in terms of the kinds of science to be accomplished. Like IODP, the OOI is a complex program, drawing together scientists from widely disparate fields, and it is difficult to cover the entire range of OOI-related science during a single meeting. The OOI is progressing rapidly with development and deployment of technology, initial funding being provided through NSF, the Keck Foundation, and other sources; the OOI is also a strong competitor for future NSF-MREFC funding. However, there is as yet no integrated science plan for combined IODP-OOI projects that interested researchers can turn to for guidance on how to plan for observatory-dependent projects, to help solicit funding from NSF-core in support of the basic survey, scientific instrumentation, or follow-up work that must be done in order to establish and operate seafloor observatories for the long term. One of the main goals of the upcoming ORION meeting is to discuss scientific objectives for the OOI and develop an Initial Science Plan (ISP) for the new program.

B. Common Goals, Needs, and Challenges

The IODP and OOI share many common goals, needs, and challenges. Both programs are relatively large in terms of needs for infrastructure investment and the numbers of scientists, engineers, and educators who will be involved. Both programs will be operated through a combination of top-down decision making and long-term planning, intermixed with grass-roots scientific proposals that are approved and implemented on a competitive basis. Both programs will allow unprecedented opportunities for education and outreach to both scientific and nonscientific audiences, to engage the population at large in missions of scientific discovery. Both programs will focus substantially on “active processes,” as opposed to reading of the geological record, although there will be interactions between process-based and record-based scientific projects within each program. Both programs will require a sustained commitment to technological development, including design, prototyping, and testing. Both the IODP and the OOI will be strengthened enormously by successes in the other. In order to maximize opportunities for success within these programs, and to help each program leverage the other, it is important to articulate and codify common scientific goals and technical needs, understand how these program could and should interact, and determine how best to plan and carry out education and outreach efforts.

A workshop was held during 17-18 July 2003, at the University of Washington, Seattle WA, to define the linkages between the IODP and the OOI. The primary aim of the workshop was to provide the scientific rationale that will underpin a broad range of scientific, technical, and educational programs involving ocean drilling and observatories.

The specific goals of the workshop were to:

(1) Articulate and codify common goals of the IODP and OOI, in preparation for a community-wide OOI meeting planned for early 2004;

(2) Identify experiments and technology necessary to achieve critical, common objectives;

(3) Establish dialog between scientists, technologists, and educators interested in one or both programs; and

(4) Encourage involvement by people who have not previously participated in planning or scientific activities for the IODP or OOI

Applications to participate in the workshop were solicited by advertisement in EOS and the USSAC newsletter, and by electronic circulation of a request for applications, and there were 65 participants (see Appendix 1 for a listing of names and contact information). This two-day workshop was planned so as to maximize time available for writing and discussion of a workshop report (see Appendix 2 for a copy of the workshop agenda). There were no scientific presentations during the workshop, and no planning for specific scientific experiments. In addition, we did not discuss the overall scientific rationale for the IODP or the OOI, since this topic has been developed extensively during other meetings. Instead, the focus of the workshop was on discussion and writing related to specific linkages between the IODP and the OOI. In addition to providing information on their background and overall scientific interests, applicants were asked submit a short abstract describing a “new experiment” that could be accomplished as part of a joint IODP and OOI effort. The focus was to be on the kind of science that could be done through the IODP and the OOI, not on specific locations where these experiments might occur. Ideal experiments will take advantage of unique opportunities provided by the IODP and the OOI, and move the science forward in a way that is not possible without one or both of these programs. The intention of the organizers in having participants suggest experiments was to illustrate a (partial) range of work that could be done through joint IODP and OOI operations, and to spark thinking about scientific, technical, logistical, and educational needs associated with this work (see Appendix 3 for a listing of these abstracts).

The morning of the first day of the workshop was dedicated to a brief discussion of the workshop agenda and goals, and overview presentations were made by representatives from ongoing and planned programs to describe current progress, future plans, and available technology. Workshop participants were divided into thematic working groups for the rest of day 1 and much of day 2. The working groups met to organize and craft their parts of the workshop report, with attention paid to three primary topics that cut across all scientific themes: (a) overall scientific goals (what are the broad questions to be addressed), (b) scientific needs (what kinds of measurements or samples, collected when, etc.), and (c) technical needs (how to make these measurements and collect these samples). Cutting through all of the scientific themes are issues related to education and outreach (E&O). As described later in this report, there was broad consensus at the workshop that E&O efforts need to be better integrated into scientific plans within the IODP and the OOI than they have been during past programs, and we remained true to this philosophy by having attendees with expertise in E&O participate in regular thematic and technical sessions. Education and outreach participants met separately during part of the afternoon of each day of the workshop to craft their own section of the workshop report.

On the second day of the workshop, informal presentations from each of the groups were followed by discussion among workshop participants, and the thematic groups separated once again to write and refine their sections of the report. There was a second set of working groups set up on day 2, cutting across disciplinary topics, based on technological and logistical needs for the new program. Once again, workshop participants with a primary interest in E&O issues were not assigned to specific technical groups, but were left to circulate among the various groups to listen to and contribute to the overall discussion. The workshop met as a full group on the afternoon of the second day, to review results from technical discussions, and to prepare overall workshop recommendations.

Draft materials prepared by each working group were left with the workshop conveners, who edited and joined the text into a single draft document. This document was circulated among workshop participants, first to the group leaders, then to the workshop group as a whole. The final version of this workshop report was completed in December 2003.

III. Background to the Programs

A. Integrated Ocean Drilling Program (IODP)

Scientific Ocean drilling has revolutionized our view of Earth history and global processes during the last 40 years. The Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) was formed in 1964 as part of a national effort to explore the geological and geophysical structure of the sea floor through a systematic program of ocean drilling, known as the Deep Sea Drilling Project (DSDP). Drilling operations during DSDP were carried out on the Glomar *Challenger* and the International Phase of Ocean Drilling (IPOD) was initiated in 1974. International participation was fundamental to the success of DSDP, and was expanded in the Ocean Drilling Program (ODP), which succeeded DSDP in 1983 and operated the drilling vessel JOIDES *Resolution*.

DSDP and ODP are widely regarded as models for international cooperation in multidisciplinary research and technological development, and the many successes of these programs contributed to the launch the Integrated Ocean Drilling Program (IODP). IODP began in September 2003, and the first IODP at-sea operations are scheduled for summer 2004. The Initial Science Plan (ISP) for IODP is titled, "Earth, Oceans and Life: Scientific Investigations of the Earth System Using Multiple Drilling Platforms and New Technologies." This document provides guidance as to the scientific and technical objectives that are of greatest interest to the new program. The ISP identifies three big-picture themes for scientific ocean drilling beyond the year 2003 [*Integrated Ocean Drilling Program (IODP) Planning Sub-Committee (IPSC)*, 2001]. The first addresses the deep biosphere and associated sub-seafloor ocean. The second involves investigating Earth's environmental change, in terms of both its processes and effects. The final theme encompasses a range of scientific problems related to the cycles and geodynamics of the solid Earth.

IODP differs fundamentally from earlier scientific ocean drilling programs, perhaps most importantly, in bringing multiple drilling platforms and new technological opportunities to the scientific community. The centerpiece of IODP's deep-drilling efforts will be a new, riser-based drilling platform (*Chikyu)* now under construction in Japan. This ship will be capable of working in deep, geologically unstable environments such as the seismogenic zone along active margins. A JOIDES *Resolution*-style (riserless) platform will also be available to IODP scientists, capable of working throughout much of the global ocean. A final component of IODP operations will be completed with "mission-specific" platforms such as jack-up rigs, barges, and other facilities that can operate in shallow water, within an ice pack, or in other specialized environments. This multiple-platform approach will allow IODP scientists to work in new areas, and address fundamental problems, that were not achievable during the previous 40 years of scientific ocean drilling.

The scientific planning and management structure for IODP is complex, as required to safely, fairly, and expeditiously handle the demands made by using multiple platforms, managing dozens of active proposals, and the needs of thousands of researchers and students working on IODP-related projects. IODP is an international partnership of scientists and research institutions and programs organized to explore Earth processes, as recorded in the ocean basins, through a program of seafloor drilling and coring, down hole measurements and sampling, and the establishment of long-term borehole observatories. IODP will contribute to collection of sediment and rock samples ("cores"); down hole geophysical and geochemical measurements ("wireline logging"); and opportunities for special experiments (both short-term and long-term) to determine in situ conditions beneath the seafloor. Extensive shipboard and shore-based facilities have been and are being developed for the study of these samples and data.

IODP is supported by "lead agencies" which are (as of the date of preparation of this report): the United States of America's National Science Foundation (NSF) and Japan's Ministry of Education, Culture, Sports, Science and Technology (MEXT). Other international partners will be added, hopefully including a European lead agency, the European Consortium for Ocean Research Drilling (ECORD). A new "Guide to IODP" is being developed by representatives of the Science Advisory Structure (SAS) to explain the management structure in some detail. Interested readers are directed to the IODP–SAS web site: (http://www.isas-office.jp).

B. Ocean Observatories Initiative (OOI)

The Ocean Observatories Initiative (OOI) is a five-year, capital acquisition project developed by the Ocean Sciences Division (OCE) of the National Science Foundation (NSF). It has been developed in response to emerging requirements for exploring the oceans in new ways, as documented in community workshops and planning reports. The OOI builds upon recent technological advances, experience with existing observatories, and pilot projects that have produced exciting results. The OOI will provide the initial basic infrastructure needed to implement an integrated system of ocean observatories, which will address the ocean science research community's growing need for sustained time-series measurements. A complete ocean observatory system would comprise most of these major capabilities [*Detrick et al.*, 2003]: continuous observations at timescales of sub-second to decadal, and spatial coverage of millimeters to kilometers; sustained operations during a wide range of local conditions (including severe weather); real-time and near-real-time communication, allowing both transmission of data and instrument control; delivery of power to permanent and temporary seafloor and subseafloor assets; access to underwater maintenance and experimental vehicles (including autonomous and remotely-operated systems); support for sensor and instrumentation development, testing, and calibration; data management; and a coordinated education and outreach effort. The OOI has been approved by the National Science Board for inclusion in the Major Research Equipment and Facilities Construction (MREFC) account of a future NSF budget request.

NSF created a steering committee, Dynamics of Earth and Ocean Systems (DEOS), to provide a focus for coordinated scientific planning, and to identify science and engineering trends, opportunities, and challenges for making sustained research-based measurements from fixed ocean observatories. DEOS advises NSF in developing the scientific rationale for the OOI, undertakes short- and long-term systems planning for the OOI, and provides essential scientific advice and advocacy to the academic community.

The OOI has three primary elements that will expand the capability to observe the oceans both spatially and temporally: 1) a tectonic plate-scale cabled observatory that spans several geological and oceanographic features, 2) relocatable deep-sea observatories based around moorings, and 3) an expanded network of coastal observatories using both fiber optic cables and moorings. The complete OOI is intended to provide cables, buoys, development platforms, moorings, and junction boxes to allow observation and active experiments near the water surface, in the water column, and on and below the seafloor. The observatories enabled by this initiative will be electronically linked and become a critical research-oriented component of the proposed Integrated Ocean Observing System (IOOS) now being developed and coordinated by Ocean.US through the National Oceanographic Partnership Program. Whereas the IOOS is motivated mainly by applied scientific and operational goals, DEOS is motivated by fundamental, inquiry-based scientific research. Both programs require long-term observations, facilities supervision, and data management. New instrumentation developed within the OOI will become increasingly important in operational systems. Ultimately, the facilities developed through the OOI are intended to support a broad scientific initiative called ORION: Ocean Research Interactive Observatory Networks. Community-wide planning for ORION will begin with a January 2004 meeting in Puerto Rico.

There have been several workshops that address various aspects of OOI development, and reports from these meetings should be of particular interest to those exploring linkages between the IODP and the OOI. A good place to start learning about the OOI is the report prepared by the Committee on the Implementation of a Seafloor Observatory Network for Oceanographic Research, Ocean Studies Board, that is currently in draft form and should be released publically in October 2003 [*Detrick et al.*, 2003]. This report summarizes many of the ideas and discussions of earlier meetings and workshops, and identifies specific needs for successful OOI development. This report includes discussion of linkages to other programs, with an emphasis on observatory efforts; however, discussion as to how the OOI and IODP might be coordinated is limited. This is the gap that the report you are reading now is intended to address.

C. Borehole Observatories in IODP

The fundamental importance of subseafloor observatories in IODP is highlighted in several ways in the ISP. Observatories figure prominently in the implementation plan for IODP, where it is noted, "*Post-drilling observations and experiments in boreholes, pioneered by ODP, will grow in importance in IODP. Sustained time-series recordings by instruments sealed within boreholes will be required to investigate active processes such as pore-water flow, thermal and chemical advection and crustal deformation. Boreholes will also be used for perturbation experiments to investigate in situ physical properties of sediments and/or crust, and their associated microbial communities. A global network of geophysical observatories for imaging Earth's deep interior is also planned.*"

The need for development of observatory capabilities within the IODP is described in virtually every section of the ISP, including discussion of the main scientific themes for the new program. One of the guiding principles for implementation of IODP is "coordination with efforts in observatory science." Planning for management of ORION is now underway, and the management and advisory structures for ODP and IODP are often cited as guiding examples of a largely-successful management approach. Thus the linkages between the OOI and the IODP extend across scientific, technical, and administrative realms.

IV. Thematic Discussions

Participants at the July 2003 IODP-OOI workshop were divided into four thematic discussion groups, with the intent of targeting areas of primary interest to both the IODP and the OOI. Some topics, such as hydrogeology and tectonics, cut across the thematic working groups. No one was excluded from participating in any group of interest, but participants in each group were responsible for drafting text covering topics relevant to their thematic group. Rather than being organized around particular seafloor settings (e.g., mid-ocean ridges, passive margins, etc.), discussion groups were process-oriented, an approach consistent with the fundamental nature of observatory science. Previous IODP and OOI meetings and workshops have focused on developing scientific justification for a broad range of scientific programs. Given time limitations, we did not attempt to summarize or recreate comprehensive earlier discussions. Instead, we emphasized fundamental questions that could be addressed through joint IODP and OOI efforts, and on the observations, sampling, and analyses required to move the science forward in a major way. Participants interested in Education and Outreach programs circulated within the Thematic panels, then met separately to draft their discussion text.

A. Earthquake dynamics, Earth structure and evolution (Thematic group leaders: *Stephen, Saffer*)

In this section we discuss Earth Science questions with an emphasis on earthquake seismology. It is convenient to consider subseafloor observatories in this area of research as comprising two main classes:

(1) Observatories that will elucidate whole Earth (deep Earth) processes occurring at very long timescales.

(2) Observatories focusing on plate boundary processes that are relatively near Earth's surface, particularly at subduction zones.

Additional observatories located at spreading centers, transform faults, and in mid-plate areas will help us to understand relations between processes that occur on larger scales (such as plate-scale stress transfer mechanisms and intraplate earthquake) and relations between processes within the lithosphere; several of these topics are discussed in the next thematic section on Lithospheric Dynamics.

1. Deep Earth Processes

A grand challenge of the twenty-first century will be to map the Earth's deep interior and to determine how this dynamic region has functioned throughout geologic time. This requires the maintenance of long-term seismic observatories in a global array encompassing both land and the ocean stations, for prolonged periods of time. Example scientific questions that such an array can help address include:

- How does surface plate tectonics interact with Earth's deep interior? Are mid-ocean ridges directly related to the main upwellings of global mantle circulation, or are they passive features towards which mantle flow is driven by plate divergence?
- How does mantle anisotropy relate to plate kinematics? If anisotropy can be used to infer the direction of flow in the mantle, what are the relationships between mantle flow and plate tectonics and dynamics?
- What is the fate of subducting slabs? Do they 'pond' at the base of the mantle? What is the nature of the D" layer?
- What are the structure and origin of hot-spot plumes? Do plumes arise from the core-mantle boundary or from other layers or boundaries within the earth?
- Does convection in the mantle occur mainly within a single layer or in multiple layers?
- How laterally heterogeneous is the mantle at various depths? Are there chemically heterogeneous zones ('continents') at the core mantle boundary? Are ultra-low velocity zones (ULVZ's), recently observed at the core-mantle boundary, sources for plume material?
- What is the structure (heterogeneity and anisotropy) of the inner and outer core, and is the inner core rotating at a different rate from the earth as a whole?
- How does the structure of the mantle and core affect the angular momentum of the earth, the length of the day and climate? What is the source of excitation for the observed continuous free oscillations (near 300sec period)? What is the origin of geomagnetic "jerks"?

Much of what we currently understand about these questions has been inferred from data collected using globally distributed seismic stations on islands and continents. With 70% of Earth's surface under the oceans, global networks will never be complete without seafloor observatories. Improved spatial sampling provided by observatories at strategically located ocean sites will provide much improved tomographic imaging of the structure of the lower mantle, the core-mantle boundary, and the role of subducting slabs and plumes in deep Earth cycling. Initial goals and a plan for this style of observatory were initiated during the ODP, and international borehole observatory efforts were coordinated through the International Ocean Network (ION) organization. Figure IV-1 illustrates the locations of sites where work has already been carried out, and additional sites that are proposed to extend the global networks across the ocean basins. In many cases such sites may be co-located with complementary sensors on the seafloor and in the water column (e.g. geomagnetic, oceanographic) that would benefit from shared power and telemetry infrastructure, logistical support, and spatial/temporal sampling requirements. Installations at many ION sites will also support topics not discussed in this section, including near-surface tectonics and other processes, and biological and physical oceanography.

There is a clear requirement for close cooperation between the OOI and IODP communities in this endeavor. Although it is possible to place seismometers directly on the seafloor, borehole installations are greatly preferred because they provide significant improvement in signal-to-noise ratio in the frequency band relevant to teleseismic, body-wave studies (periods shorter than a few seconds). A number of seismic studies over the past 15 years have demonstrated the benefits of seafloor borehole installations to reduce ambient noise and improve coupling of seismometers to true earth motion (Fig. IV-2). Above the microseism peak (in terms of frequency), borehole sensors give considerably improved ambient noise compared to seafloor and buried sensors. In this experiment the borehole sensor was subject to noise created by fluid flow in the well. Other experiments in which borehole flow has been blocked by glass beads or the sensors have been cemented in place have comparable or lower noise than the buried sensor. Overall the detectability of earthquakes using borehole sensors is an order of magnitude better than using seafloor sensors (Sutherland et al., 2004). Borehole installations are necessary for the collection of critical data for body waves sampling the deep mantle (P waves) and the core (PKP, PKIKP). In order to obtain global coverage, some of these boreholes will need to be in the extreme high latitudes of the Southern Ocean, where operations are very difficult.

Widely-spaced boreholes (about 2,000 km separation) that penetrate sufficiently deeply into basement (≥100 m) are required to provide clean, well-coupled signals of deep-Earth processes and properties are required. Because it is a source of unwanted noise, fluid flow around the borehole seismometer must be stopped by a combination of casing, cement, and glass beads (or similar approaches). There will be band-width, noise, and power issues depending on the ultimate design of the borehole sensors. Depending on the geographical location, the observatory function may be met by buoys, retired telecommunications cables, new fiber optic cables, or autonomously recording seafloor data acquisition packages.

Ocean drilling assets will be required to create boreholes for many of these seismic stations, and drilling platforms may be needed for sensor installation and servicing in many cases. Care should be taken during observatory design to optimize opportunities for 'piggy-backed' scientific experiments, while not compromising the primary goals of these stations.

2. Subduction Zone Dynamics

A close interaction between IODP and OOI communities is expected in plate boundary environments (ridges, transform faults, and subduction zones), to emplace seafloor instruments and observatories to make direct measurements of parameters such as seismicity, strain, and pore pressure in boreholes and to monitor these quantities continuously. Subduction earthquakes release 90% of Earth's seismic energy and generate some of the largest earthquakes on the planet. These events pose a serious risk to a large fraction of Earth's population living in coastal areas. Key measurements will come from near the earthquake source regions. These studies will dovetail with principal objectives of the IODP's seismogenic zone drilling projects and the SEIZE objectives of the NSF OCE MARGINS program.

Offshore geodetic and seismological monitoring programs are vital to characterize locked regions of subduction zones capable of generating large and damaging earthquakes. Unfortunately satellite data cannot be used off shore to measure seismic strains and available GPS and seismological station coverage often includes only a small portion of the deeper locked region that lies below land. In addition, both existing GPS and the seismic stations are asymmetrically distributed landward of the region of interest. This greatly reduces the positional accuracy and resolution of earthquake locations and geodetic studies of seismogenic fault segments. Finally, there is a lack of direct in situ observations – both long-term and instantaneous - of almost every parameter relevant to fault and earthquake mechanics (i.e. strain, pore pressure, fluid chemistry, etc.) over much of the submerged system. Together these deficiencies greatly limit our ability to understand the dynamics of subduction earthquakes.

An example this limitation is our lack of understanding of subduction earthquake dynamics. Subduction megathrusts exhibit a wide range of slip behaviors, not limited to aseismic creep and coseismic rupture, but including “silent slip”, or “ultra-slow earthquakes”, and earthquake afterslip. These slow slip events can even occur along strongly-coupled subduction interfaces. Most silent earthquakes that have been identified to date occur in the deep, aseismic region that lies below land-based stations. Perhaps they are limited to such depths but their depth distribution may simply be biased because ultra-slow silent earthquakes generally are not being tracked at shallow depths offshore using seismic and GPS techniques.

Seafloor borehole observatories will allow researchers to address many long-standing questions related to seismic processes at subduction zones:

- What causes the upper transition from aseismic to seismic slip? This is a critical and fundamental aspect of subduction zone earthquake behavior, with important implications for ground shaking and tsunami hazard evaluation – yet it remains poorly understood. There are a wide range of geologic processes posited to cause this transition, including clay mineral transformation, diagenetic processes, increased lithification/consolidation, and increased effective stress perhaps mediated by spatial changes in pore pressure. Integrated IODP and OOI observatory elements can directly address this question by better locating the position of the transition, and correlating it with downhole observations, measurements, and sampling.
- What are the temporal relationships among stress, strain (seismic and aseismic), pore fluid pressure, and chemical composition throughout the earthquake cycle? What is the role of stress triggering and pore elastic effects within and between plate boundaries, and how are these processes related across long distances and between events?
- How does the earthquake cycle depend on the nature of asperities and their evolution? What is the degree of coupling in the offshore area of subduction systems? Does the degree of fault coupling (i.e., locked or partially locked) determine the subsequent distribution of moment release? Do asperities move or remain stationary between earthquake cycles and why do they do so? What controls the updip and downdip limits of seismicity?
- What are the relative roles of seismic and aseismic moment release mechanisms (e.g., silent earthquakes) during seismic cycles? Are these mechanisms spatially associated with particular regions on plate boundaries or do they migrate with time? What controls propagation

and slip rates of earthquakes and the distribution of fast, slow, tsunamigenic, and silent earthquakes?

- Are there pre-rupture phenomena that occur during the initiation of earthquakes?

The complex behavior of active systems and feedbacks between processes at a range of depths and timescales requires an integrated approach that includes direct borehole observatories, seafloor observatories, and remote geophysical methods. Broad arrays of surface instrumentation and boreholes are required. The combination of OOI and IODP methods and technologies will provide unparalleled opportunities to address the questions listed above.

Approaches to resolving these questions may involve: pre-, syn- and post-event and observatory emplacement and site characterization, including subsurface studies and measurements (seafloor video, seafloor flux meters, seafloor geodetics, arrays of shallow or seafloor seismometers), subsurface geophysical and chemical studies including borehole observations and characterization (cores, logging, seismicity – strings of instruments, strain accumulation, fluid pressure, flow rates, fluid chemistry, temperature etc.); and repeated geophysical surveys (E-M, seismic, Figure IV-3). Such studies must also be closely integrated with (and to some extent, directed by) theoretical modeling and laboratory work. Rapid response and continuous monitoring capabilities would allow post-earthquake observations during critical times. For example, continuous monitoring will allow assessment of changes in fluid fluxes or chemistry at the seafloor that indicate processes occurring at depth. Similarly, results from repeated surveys (3-D and 4-D) could be related to in-situ subsurface conditions through direct observations.

The character of the seismic reflections can vary with time for at least three reasons: 1) when the state of stress on a horizon of interest varies with time a) as a result of an earthquake on the fault (over seconds), b) as a result of an earthquake in the region which changes the regional stress pattern (Coulomb stresses, over days, months and years), or c) as a result of slow deformation (over tens of years); 2) when the drilling process itself changes the *in-situ* pressure conditions on the fault by relieving whatever pressure anomaly may have originally existed (over hours to years); and 3) when the seismic acquisition system changes. Reasons 1) and 2) have significant geological consequences and will affect the application of seismic methods to understanding plate boundary processes. Reason 3) is a common phenomenon, and illustrates why it is good practice in time lapse surveys to change as few aspects of the acquisition system as possible.

B. Lithospheric dynamics, geodetics, heat and fluid transport (Thematic group leaders: *Becker, Trehu*)

The primary focus of lithospheric geodynamics is understanding of the processes that lead to formation, evolution, deformation and destruction of the lithospheric plates. Plate evolution influences the chemical and mass balance of the ocean as a result of mass and heat fluxes across the seafloor. Although it is often assumed that plate interiors are seismically inactive, recent studies highlight the potential importance of seismic events in lithospheric evolution. Scientific ocean drilling has been an essential tool for sampling and instrumenting the subseafloor lithospheric environment.

Much has been learned in the past several decades about continental rifting, seafloor spreading, plate flexure, intraplate earthquakes, and other related processes. Recent studies have led to a new understanding of the episodicity of plate formation over a wide range of spatial scales. Spreading episodes, strain relaxation pulses, thrust events at subduction zones, etc., are transient events with repeat intervals measured in years to centuries. Critical information about the physical and chemical response of the lithosphere to change is being lost because we lack a continuous, flexible presence in places where important events occur. In this section, we discuss how implementation and coordination of the IODP and the OOI (along with other programs) will lead to major advances in understanding oceanic lithospheric plate dynamics.

The NSF/RIDGE 2000 (R2K) Program of Integrated and Time-Critical Studies includes a detailed plan of action to address remaining questions about the creation of new oceanic crust. Projects under the R2K program will deploy arrays of seafloor instruments and experiments, collect samples, conduct surveys (geophysical, water-column, seafloor imaging), and monitor seismicity, deformation, and properties of seafloor hydrothermal vents at 3-6 geologically diverse spreading ridge sites over a 6-12 year period of time. A unique opportunity exists for the IODP and the OOI to make these studies four-dimensional by drilling arrays of holes in the selected site areas, and establishing subseafloor observatories that complement the seafloor and water column experiments and observations. Many of the objectives will be further served by the increased power, greater bandwidth, longer sampling times, and real-time access enabled by planned OOI facilities. Some examples of exciting cross-fertilization between these programs might include the following:

- Four-dimensional exploration of microbial diversity, distribution, and abundance (see Thematic section C);
- Drilling and instrumentation to ground-truth the physical and chemical nature of seismic reflectors, regional velocity structure, variations in fluid flow, and electromagnetic properties of the crust;
- Studies of fluid flow dynamics, geometry of circulation, and the dispersion of vent plumes utilizing the injection of chemical tracers (inert and reactive) in boreholes. Subsequent monitoring at depth,, in vent fluids and the water column) would allow us to understand chemical dispersion and chemical residence patterns as small to intermediate plate scales (meters to kilometers).
- Establishing subsea communications and programming of instruments and AUV's to permit automatic onset (or increased frequency) of measurements/imaging/sampling on and within the seafloor when seafloor or borehole instruments detect events.
- Using arrays of shallow holes instrumented with seismometers and geodetic instruments for enhanced detection of microseismicity and deformation, while monitoring any corresponding temporal changes in seafloor venting.

Numerous recent studies have illuminated the critical roles that fluid flow plays in influencing the evolution of the lithosphere and of the ocean. For example, flow within the lithosphere from ridge crests to ridge flanks contributes to enormous heat loss from aging plates, regional to local redistribution of heat, massive solute fluxes to and from the plate, inputs of volatiles at subduction zones, and cycling of oxygen and nutrients to considerable depth below the seafloor. Studies demonstrate that fluid regimes within the plate are highly heterogeneous and compartmentalized (physically, chemically distinct), despite evidence for transport over enormous distances (kilometers to tens of kilometers or more). But there remains considerable uncertainty as to how much of the crust is involved in active circulation at any time, and how ridge-crest and ridge-flank hydrogeologic systems are related. Understanding the nature of subseafloor fluid flow systems requires determining long-term histories of in-situ temperature, pressure, fluid chemistry, and microbiology.

Analyses of these records yields information on: reequilibration of boreholes following drilling; hydrological transients; large-scale formation hydraulic properties from subseafloor tidal loading, tectonic events, and other perturbations. For example, researchers were surprised recently to see pressure responses in four seafloor observatories installed on the eastern flank of the Juan de Fuca Ridge as a result of seismic activity along the distant Nootka Fault, a strike-slip transform plate boundary. Interpretation of these data provided large-scale estimates of aseismic strain and crustal hydraulic diffusivity. These kinds of studies will be greatly enhanced by linked IODP and OOI efforts, including: increased sampling rates and data storage; power for in-situ perturbation experiments (heat, fluid, tracer); the ability to respond to events by command and control; allied seafloor monitoring instruments; and added sensors downhole (e.g., seismometers, strain meters). Above all, the combination of IODP-OOI efforts will allow temporal monitoring of state and processes in multiple dimensions, greatly improving our ability to separate cause and effect of active processes.

Tectonic activity within plates is likely to increase in frequency and magnitude when the plate approaches the subduction zone, as the plate flexes. This should result in profound changes in crustal (even lithospheric) properties and fluid and heat fluxes, and is likely to influence tectonic and slope processes in the overlying plate following subduction, and the extent of volatile transport with the downgoing slab. There may also be important relations between crustal tectonics and long-scale fluid transport within subduction zones, including the extent and locations of gas hydrate deposits. Similarly, seismic activity along transform faults may open fractions and allow invasion of seawater, greatly influencing the extent of serpentinization, and crustal shear strength, velocity and density. The significance of serpentinization at subduction zones, particularly within the incoming plate as it is flexed outboard of the trench, is another topic of considerable interest. Studies of all of these problems will be enhanced through better coverage of intraplate regions via expansion of global borehole network, including monitoring of seismic, thermal, fluid, and microbiological processes.

The nature of mid-oceanic plate seismicity also remains largely unexplored, in part because events tend to be small in magnitude, and generally there are not instruments in place for long enough, with the right sensitivity, to detect these events. There are important exceptions, particularly in continental areas where interplace earthquakes can be devastating (e.g., Charleston, New Madrid, and Lisbon). More recently, there was a large interplate, oceanic seismic event south of Australia (Balleny Island, 1998). There is very little bathymetric coverage in this area, so the locations of significant fracture zones and other features are poorly known. Both the location and the focal mechanism of this event (and associated aftershocks) are poorly determined by the global array. Similarly, large earthquakes that are known to occur along fracture zones are generally poorly located. Thus the establishment of a more extentive global array of seafloor and subseafloor seismic stations can help to address problems related to both deep Earth structure and near-surface tectonics.

To understand better the seismogenic nature of oceanic lithosphere as it deforms internally and slips on major transform faults is challenging, given the typical frequency of events at any given location relative to realistic observational epochs. The chances of capturing seismic events can be improved by focusing efforts in areas characterized by high rates of seismic energy release, and they can be further increased by occupying these areas with local arrays that are scaled appropriately to the structure of interest. Even in areas of high average activity, observations of events of limited temporal density are more likely to be made if the geographic distribution of observation points is increased. There are other important advantages to taking this approach: earthquake focal depths, rupture characterization, aftershock distribution, and magnitude thresholds are all improved through array observations, and co-located complementary observations such as crustal strain and formation-fluid pressure can take equal advantage of the borehole sites used for the seismic array.

The importance of complementary measurements cannot be overstated. It is well known that the mechanical properties that control the strength and mode of failure of the crust and upper mantle are stongly controlled by temperature and interstitial fluid pressure. Hence, whatever that can be done to characterize the thermal and hydrologic regime in areas of seismic activity should be done. This includes detailed site characterization via temporary seismometer deployments, seismic reflection profiling, and heat-flow transects, and both short- and long-term geophysical and geochemical borehole observations, and observations in the overlying water column (Fig. IV-4). This will allow multi-dimensional (chemical, thermal, hydrologic, seismic) characterization of lithospheric processes that occur at depths ranging from the uppermost crust to the deep mantle.

Although they are generally smaller than events at active margins, and less frequent than events at spreading centers, mid-plate events also play an important role in crustal-scale fluid transport and act as indicator of regional stress transference. Studies in the marine environment have tended to focus on correlations between magmatic, tectonic and hydrologic processes on a local scale, because of the local nature of the available data sets. However, studies of hydrothermal systems on land, which have access to a variety of continent-wide data networks, suggest that distant earthquakes affect local hydrology over extremely long distances. Acquisition of synoptic plate-wide observations of seismic activity, strain, and hydrological properties from a single oceanic plate has the potential to reveal the mechanisms responsible for these plate-scale processes. A better understanding of such long-distance stress propagation, in turn, has the potential to lead to major advances in understanding what triggers major natural hazards such as subduction zone earthquakes and tsunamagenic slope instability, and eventually developing effective warning systems.

C. Microbiology, geochemistry, paleoceanography (Thematic group leaders: *Cowen, D'Hondt*)

Researchers are just beginning to assess the nature of the subseafloor chemisphere and biosphere, the composition and structure of microbiological communities, necessary fluid and nutrient fluxes, and rates of reproduction and biomass generation. There are also efforts underway to elucidate the roles of the subsurface biosphere in the global carbon cycle. The overarching question that has prompted many of these studies is: What conditions and processes drive change in subseafloor geochemical compositions and the structure and extent of the subseafloor biosphere?

Strong active linkages exist among geochemical, microbiological, hydrological, geophysical, and oceanographic processes. For example, local geochemical conditions and processes strongly influence microbial community structure and metabolic activities. Hydrological properties of the environment, such as permeability and flow rates, control water-rock reaction rates, rates of substrate delivery and metabolite removal, and cell mobility. In turn geochemical and biological diagenetic processes affect permeability and flow rates. Tectonic or magmatic events can strongly alter the hydrological system (e.g., fluid flow patterns, thermal and chemical gradients) resulting in dramatic changes to the distribution of microbial habitats. Accordingly, interdisciplinary cooperation is critical throughout the design and implementation phases of IODP-OOI borehole observatories (both during drilling/observatory deployment and during long-term operation of these systems).

One initial challenge has been to recover material with minimal contamination so that it can be studied under controlled conditions in a laboratory. However, a new approach is now being developed: in-situ culturing and analysis. Through establishment of borehole observatories and related systems at the seafloor, it may soon be possible to examine the dynamics of microbiological systems without the disruption that inevitably occurs when seafloor and subseafloor material is sampled and brought to Earth's surface. There will be important contributions made from both surface laboratory and *in-situ* studies in the next decade, but opportunities for subseafloor experiments are particularly exciting.

Sampling of pristine formation fluids within permeable subseafloor environments has been a goal of ocean drilling since the early days of DSDP. The fundamental difficulty is that any formation that is permeable enough to host significant fluxes of fluid, heat, and solutes is also likely to be strongly invaded by fluids used during drilling, generally surface seawater (sometimes mixed with mud) as well as rust, pipe grease, and other contaminants. One approach is to hydrogeologically seal the subseafloor environment and allow geochemical reequilibration over a period of months to years. A related option is to drill into regions where fluids are thought to be overpressured, and then allow the formation to produce sufficient fluid (over weeks or more) to flush out the invaded zone. However, there remain difficulties with avoiding contamination as the fluid passes through and reacts with screens, casing, and tubing between the formation and the seafloor.

Specific microbiological, geochemical, and paleoceanographic questions that will require a combination of IODP and OOI approaches include:

- What organisms are present beneath the seafloor? How abundant are they? What do they do for a living? How active are they? What are their microbial interactions? How do subseafloor organisms affect their environments?
- What are the mass fluxes of water and chemicals in/out of ocean crust and continental margin environments?
- How do subseafloor biological communities and activities and geochemical compositions and processes vary in time and space?

• What is the evidence for short-term (annual to decadal) and longer changes in bottom water temperatures, and what can these data tell us about global change and the stability of bottom currents?

One of the first goals of time-series studies of the subseafloor biosphere is to determine the nature of microbial diversity. This requires detailed time-series sampling and analysis, following return to “natural” or dynamic steady-state conditions. There also must be complete characterization of the biogeochemical environment, and an assessment of rates of biomass production by chemosynthetic and heterotrophic processes. Finally, there should be an assessment of organic and inorganic energy sources, origins, and supply rates.

In oceanic plate environments, subseafloor observatories are similarly essential for accurate assessments of the relative distributions of fluid and solutes fluxed between ridge, flank, and basin environments, and an assessment of how these fluxes are conveyed within the crust. In active and passive margin environments, there are many questions pertaining to biological interactions with hydrate-bearing sediments, active tectonics, and shallow shelf and slope hydrologic systems. Observatories will help us to assess how geochemistry and biology varies from one subsurface environment to another, how parameters respond to natural environmental changes (e.g., variations in temperature, heat input, fluid/chemical fluxes, tectonic/magmatic activity, lithology, and the nature of fluid flow pathways), how they respond to human perturbation (e.g., drilling, circulation, introduction of oxygen or nutrients), and how the subsurface is linked to overlying (oceanographic) conditions and communities.

There must also be studies of how subseafloor biological activity affects solid chemistry, pore fluid chemistry, fluid, heat, and solute circulation, as well as chemical and biological fluxes to the ocean. This will require determining how nutrients and biomass are cycled within the seafloor and between the seafloor and overlying ocean, and the roles of the subseafloor biosphere in global biogeochemical cycles and long-term global change.

Within the realm of paleoceanographic studies that might be addressed through observatory experiments, the guiding question is: how have deepwater conditions changed in the past and influenced global climate? Numerous studies of borehole temperatures on land have led to one of the most important, direct lines of evidence for global climate change during the last several hundred years. These studies have demonstrated clearly that, on average, global temperatures increased by ~0.6 °C during the 20th century. Similar studies have yet to be attempted on the seafloor, although the relatively stability of seafloor temperatures in many settings may allow real-time evaluation of global change. This concept remains to be tested in an appropriate setting using available technology.

Borehole observatories could be installed along a subseafloor flow path to document biological and chemical change (Fig. IV-5). This experiment could address processes related to fluid flow along mid-ocean ridge axes, ridge flanks, subduction zones, and along continental margins where ground water flows into the ocean. Boreholes would be required to penetrate hydrologically-active zones. These zones would be sealed and instrumented to monitor changes that were induced during drilling. Once holes reach thermal, chemical, and biological "steady state," holes could either be incubators for additional studies or would be altered (e.g., extraction or injection tests) to examine the response to biogeochemical perturbations. Hole-to-hole tests along a transect provide a quantitative assessment of hydrologic pathways, thus allowing extrapolation well beyond the boreholes.

A novel type of experiment enabled by the linkage between OOI and IODP consists of measuring in situ microbial activity. A substrate can be injected into the borehole and extracted over time to see if the substrate is metabolized and determine if there is a microbial response (Fig. IV-6). Many different types of substrates and reactants can be used including electron donor/acceptor couples, radiogenic tracers, or stable isotopes. The key is that the substrate should stimulate a metabolic reaction (sulfate reduction is one of many examples) such that the concentration of the substrate decreases over time and the concentration of a metabolic product increases. Such experiments could be conducted in seafloor sediments or hard-rock basement with single or multiple borehole systems. Successful experiments will lead to great strides in the understanding of the importance of subsurface microorganisms to global biogeochemical cycles.

A number of hypotheses related to subsurface microbial ecology can be addressed with in-situ cultures. For example, do microbes use inorganic metabolic substrates and can they use metabolic substrates bound in minerals? Other questions that can be addressed with *in-situ* cultures are (1) do microbes release or sequester elements such as C, S, and P, and (2) do microbes alter igneous rocks? Batch and flow-through microcosms can be used to address these questions. Batch microcosms can be incubated in situ to duplicate the pressure and temperature conditions in the crust. Flow-through microcosms duplicate pressure, temperature, and fluid composition. Substrates in the microcosms can be hydrogen, methane, ferrous iron, ferric iron, manganese, hydrogen sulfide, various organic compounds, amino acids, primary igneous minerals and glass, secondary minerals, and mineral sulfides. Sources of carbon, nitrogen, phosphorus, and micronutrients can also be varied. Microcosms are left in place for periods of days to years and then recovered. They can be placed in the borehole or at the sea floor. Seafloor deployment requires pumps to bring formation water to the microcosms and heaters to maintain subseafloor temperature. The advantage of seafloor deployment over downhole deployment is relative ease of recovering the microcosms.

Drilling of ocean crust can be expected to severely perturb the biological communities of crust in the borehole vicinity. As the physical and chemical conditions of ocean-crust boreholes evolve toward crustal conditions from open-hole conditions, the biological communities and activities in the holes presumably also change. Under ideal circumstances, as the physical and chemical environment stabilized in individually segregated intervals of a CORKed hole, the biological communities might grow to closely resemble native crustal communities. Factors that are likely to influence successions of communities and activities within the CORKed hole include (1) evolution of the chemical and physical environment within the hole, and (2) removal and introduction of cells by hydrologic flow within the ocean crust. The evolution of the environment and the succession of biological communities can be directly documented by long-term monitoring of physically isolated intervals of CORKed boreholes. Properties of particular interest for such long-term monitoring include the chemical and physical characteristics of the CORKed environment, chemical signatures of net metabolic interactions, rates of in situ activities, genetic evidence of the organisms present in the environment, and direct evidence of the organisms active in the environment.

In sedimented sections where biogeochemical processes actively alter the surrounding matrix, experiments need to be conducted with minimal disturbance to the sediment matrix. For this type of experiment the drillship would be used to push instrument packages well into the sediment at depths below that achievable from typical piston coring operations. Instrument packages loaded with physical, chemical and biological sensors will be designed to sample the environment or perturb it to elucidate sediment diagenetic and microbial processes. These deployments could be deployed in areas with active pore water flow or those areas without flow. Connections between these IODP instruments to seafloor observatories would allow access to data and samples, and provide a critical link across the seafloor interface.

Knowledge of bottom water temperature (BWT) variations is important to understanding the nature and vigor of ocean circulation as well as the nature of climatic interactions between the ocean and atmosphere. Because marine sediments have a low thermal diffusivity, variations in BWT propagate slowly downward through the sediments perturbing the background thermal field. These temperature perturbations can be used to reconstruct BWT histories. By measuring thermal transients as a function of time at a borehole observatory, the transient component of the BWT variation can be directly isolated and compared to measured variations in BWT. These measurements and reconstructions could be used to calibrate proxy methods for determining BWT variations. The possibility of reconstructing BWT histories with sufficient resolution creates the potential for BWT reconstructions across climatically important gateways.

Collectively, these experiments will require measurements and sampling of these parameters and materials: organismal diversity (nucleic acids, lipids and other biomarkers), biomass, in-situ rates of metabolic activities, concentrations of dissolved major and minor ions, dissolved electron acceptors/donors (inorganic and organic redox species), dissolved carbon sources (organic compounds, CO_2), dissolved nutrients (e.g., PO_4, NO_3), isotopic ratios, pH, temperature, hydrologic properties, and fluid fluxes.

D. Methane (hydrates), slope stability, sediment transport (Thematic group leader: *Torres*)

Combined IODP-OOI efforts will provide significant advances in our understanding of how slope systems respond to oceanographic and tectonic perturbations. By definition, these are dynamic systems that require long-term monitoring of interdependent parameters over a range of spatial and temporal scales. Two examples of processes-oriented studies that require integrated ocean drilling and observatory capabilities are: 1) the contribution of seafloor carbon fluxes (via methane) to the global carbon budget and associated climatic effects, and 2) the spatial distribution and dynamic behavior of gravitationally unstable regions. Submarine slopes can destabilize either because of increases in applied shear stress (e.g., oversteepened gradient, dynamic loading by earthquakes or storm waves) or because of decreases in shear strength (i.e., cohesion, coefficient of internal friction, effective normal stress). One common mechanism that leads to slope instability is the build-up of excess pore pressure generated by aqueous fluids and/or gas. Thus, methane gas and hydrates link these two topics.

Methane gas and hydrates are fundamental parts of the natural carbon cycle, but much remains unknown regarding their contributions to the global budgets; the processes leading to methane generation, transport within the sediments, hydrate formation, and release at the seafloor; and methane consumption via anaerobic and aerobic microbial oxidation. In continental margin settings with high methane concentrations, gas hydrates will naturally occur at depths >300-500 m. In these regions, the feedback between oceanographic and tectonic forcing is likely to be even more complex, with multiple processes operating simultaneously over a wide range of time scales. Although the existence of gas hydrates has been known for decades, their potential impacts on slope stability, carbon cycling, and more provocatively, climate change are just beginning to be appreciated. To understand the role(s) of gas hydrate in the carbon cycle it is important to study and compare the observations at both convergent and passive margins, low flux and high flux environments, areas characterized by various geophysical signatures (e.g., strong versus weak BSR), and sites with different sediment stratigraphy.

Numerous laboratory and field studies, including several ocean drilling expeditions in the past decade, have provided critical background data on the conditions of gas hydrate stability and instability, and an overall view on the composition and distribution of gas hydrates worldwide. These results also stimulated the modeling of potential feedback mechanisms between hydrate dynamics, slope stability, and climate change. However, key questions remain unanswered and can only be addressed only through integration of IODP and OOI efforts:

- What are the dominant processes controlling methane dynamics (including hydrate formation), and their relations to fluid flow and pore pressures? What is the impact of transient events associated with multi-phase flow, cementation (both hydrate and carbonate), seismicity, and slope failure?
- Are the rates of carbon discharge from margin sequences relatively constant or highly variable over a range of time scales, and what controls fluxes?
- What are the triggering mechanisms (e.g. seepage forces, seismicity, storm loading, hydrate disassociation, temperature changes, etc.) that lead to slope failure, and what is the system response to these events? How do these events influence regional and global climate?
- Do many continental margin slopes continually creep or do they fail mainly during discrete events? How do we assess tsunamogenic potential (distribution, degree of instability, risk factors) of unstable margin sequences and likely triggering conditions?

The success of relevant experiments in addressing these issues requires highly interdisciplinary experimental designs. Hydrologic, microbiological, geotechnical, geochemical, and seismologic issues are pervasive throughout the discussion of carbon cycle, hydrates, and slope stability; thus observatory designs must be integrate these disciplines. As another example, studies of sediment transport and redistribution in the near seabed environment can be addressed with a combination of drilling and seismic surveys to provide geological context, with seafloor time-series observations of sediment transport provided by long-term instrument deployments and sampling.

Hydrate observatories need to include instrumented boreholes to allow long-term observations of operating relationships among physical, chemical, and biological processes via coordinated time-series observations and sampling. Required capabilities must allow for borehole-to-borehole experiments (including use of fluid tracers), temperature, pressure, fluid geochemistry, gas exchange, carbon cycling, and microbial interactions. Studies aimed at understanding the baseline behavior of the system must be undertaken before perturbation experiments are performed.

Examples of system perturbations to observe hydrological, physical, chemical and biological responses may include: (a) thermal destabilization and monitoring of chemical changes (e.g. oxygen, DIC and DOC) and biosphere response; (b) cooling a system below a BSR to observe hydrate formation; or (c) pumping of reduced fluids to the seafloor in "artificial seeps," to study responses of the biosphere. Important contributions from cabled observatories at these sites would be the access to power, which is currently a limiting factor for experiments involving pumping and heating. Pumping is essential to sample formation fluids for chemical characterization, to develop microbial culture experiments, and to conduct hydrological tracer experiments. Heat is needed for perturbation experiments as well as to prevent instruments from freezing due to gas hydrate formation. Perturbation experiments can be conducted in areas where hydrates are present in order to understand the sensitivity of the interplay between changes in environment and hydrates.

For example, one technically-challenging set of questions involves assessing how hydrates respond to changes in bottom water temperature associated with regional or global warming. The observatory plan needs to be integrated with the development of appropriate models that will guide experimental design, enhance data interpretation, and allow for experiment modifications in an iterative process.

Although the geomorphic products of ancient mass-wasting events can be mapped using seismic-reflection and multi-beam systems, little is known about the distribution of potentially unstable regions offshore. Slope stability is governed by the balance between: (1) driving forces: gravity, seepage forces, changes in slope angle, earthquake acceleration, storm waves, erosion of lateral support, benthic storms; and (2) resisting properties: basal friction along potential failure surfaces, precipitation or dissolution of cements (including methane hydrate), elevation or reduction of pore (water or gas) pressure, and remolding. Since some mechanisms might be more influential than others in different environments, we need observations from several settings to discriminate among various causes and effects. Examples of type localities include the walls of canyons, seeps, large landslides where multiple events might occur, and well-characterized sites of small-scale slides that might be analogs for larger systems. A slope stability observatory might consist of an array of boreholes to monitor driving mechanisms (oceanographic and tectonic), the physical state of the system and triggering mechanisms (pore pressure), and complementary boreholes and surface measurements designed to monitor slope response (creeping, episodic motion).

V. Education and Outreach (Thematic group leader: *Gröschel*)

A robust education and outreach (E&O) program is considered essential to the scientific and technological successes of both the OOI and the IODP. E&O activities will increase awareness and understanding of the science and technology used in ocean drilling and long-term observatories, as needed to secure a long-term commitment to funding, and make a positive sustainable impact on science education and society. The sense of discovery and ideas, the story of the human endeavor at sea, the concepts of Earth history and processes, and the availability of real-time data can be used to promote inquiry-based learning at all levels. Success in E&O will not only expand classroom, museum and online involvement in ocean sciences, but will also provide access to underrepresented stakeholders and provide opportunities for funding of future OOI- and IODP-related projects.

There was spirited discussion at the workshop regarding how best to communicate scientific and technical results to the public at large, and to a wide array of scientific communities, but there was consensus that such efforts are extremely important. This conclusion is entirely consistent with recommendations from the recent IODP Education Workshop (May 2003) that there should be clear commitments to integrated education and outreach efforts during the initial phases of planning for the new programs. There has been a tendency within many Earth and Ocean Science programs to treat E&O as an afterthought, and to separate the development of E&O activities from the fundamental scientific planning process. In part this arises from a sense among many scientists that they are not qualified to undertake E&O efforts, that E&O efforts are not valued or rewarded within academic circles, and that E&O programs divert valuable resources that could otherwise be applied to scientific and technical needs. The first two concerns can be addressed through development of E&O capabilities within the two programs, including the support of dedicated, experienced staff with the right mixture of scientific, technical, and educational skills. The third concern is largely a misperception and a self-fulfilling prophecy: poorly-planned, inadequately-funded E&O efforts are unlikely to be successful and thus will not help to maintain and generate interest and resources. E&O must be viewed as an *investment* that will generate substantial returns for scientists involved in the IODP and the OOI, and will help to generate continued (perhaps even increased) support over the lifetimes of these programs. There is a need to look at successful E&O efforts run through NASA and other entities, develop long-term strategies for creation of successful E&O efforts within the IODP and the OOI, identify at early stages those scientific programs and investigators most amenable to E&O efforts, include E&O development at all levels of planning, and educate the IODP and OOI scientific communities as to how these efforts will yield benefits in the long run.

Workshop discussions with in the E&O group focused on several major topics. Prioritization of target groups, and adaptation of approaches specific to the unique aspects of the OOI and the IODP, should be based on the successes of other major ocean science education and outreach programs. The assessment of the human and financial resources needed to plan, implement, and fund E&O activities is of particular importance. K-16 educators (teachers, informal educators, curriculum developers, and administrators) need to teach science while meeting the daunting national and local educational standards, so there will need to be careful attention to creation of appropriate materials. The E&O group identified many linkages between elements of the science and technical fields discussed at the workshop and the U.S. National

Science Education Standards (NSES). The use of OOI/ IODP content would be an exciting way to meet science and technology standards and bring Earth and Ocean science into the classroom.

Several questions require further discussion as the OOI/IODP relationship matures.

• What key scientific questions common to both programs will most readily lend themselves to E&O?

• What significant technologies have emerged from observatory and ocean drilling science?

• What technology may be required in the future to answer scientific questions?

• How can E&O best promote OOI science and technology and its relevance to societal concerns and challenges?

A. Education and Outreach Strategies

The following strategies and philosophies are suggested as a starting point for ongoing discussion among those responsible for linked E&O efforts:

• Present observatory and ocean drilling science content to a broad audience, and emphasize the unique sense of discovery and international cooperation that characterize OOI/IODP.

• Develop and maintain an effective website with distinct resources for K-16 educators, students, and the public that includes, but is not limited to, authentic data sets that can be used for inquiry learning.

• Provide pre-service, in-service, and in-residence programs for K-12 teachers that are synergistic with national and local education standards. Look for connections with existing education curricula that were designed to meet the National Science Education Standards (NSES). Develop new, stand-alone materials that focus on OOI/IODP E&O themes and also meet the NSES.

• Focus K-12 education efforts on middle school students in grades 5-8.

• Continue and expand existing, successful Ocean Drilling Program activities for undergraduate and graduate students and educators.

• Try to avoid redundancy with existing E&O efforts within the ocean sciences community by adopting successful models and exploring partnership opportunities with other

NSF-funded ocean science education centers and initiatives. Be aware of local, existing E&O efforts, but think at a larger scale to inform a national audience.

- Reach out to teachers at National Science Teachers Association (NSTA) events, other professional organization meetings, and informal settings (museums, departments of education).
- Emphasize the relationship of successful OOI/IODP science, and the evolution of new ideas, with new uses of technology and the important roles of engineering, computing, and communications.

B. Education and Outreach Organizational Structure

Organizational needs for OOI/IODP were discussed on the basis of short-term goals (to be included in planning and management documents for the OOI and ORION) and longer-term goals. We note that these approaches are fundamentally different from what has been done in the past within DSDP and ODP, but emphasize that changes are needed to obtain the maximum benefit from these efforts.

In the immediate term, E&O efforts should be elevated within the planning and operational structure to have a status commensurate with science and engineering efforts. By this we mean that the potential for E&O activities resulting from individual programs should be assessed at an early stage of project development, and a relatively high level of staffing should be assured. For example, the NSF currently requires that proposal PIs address the “Broader Impacts” of their work, and reviewers are asked specifically to comment on this aspect of each proposal. We see no reason why proposals to the IODP and the OOI should not include similar justification. This would not be the primary criterion by which successful proposals are selected, but it would be helpful to have scientists think in these terms as they develop projects. Experts within the programs could then assess which programs offer the best prospects for E&O efforts. We do not envision that all projects will have comprehensive E&O components, but decisions must be made at an early stage in planning so that those programs that could provide outstanding opportunities are given a chance to do so.

An E&O Advisory Committee of scientists, engineers, technology experts, and educators should be established as soon as possible to develop and implement a viable, vibrant E&O plan. This plan should include mechanisms for identification of candidate projects. E&O staff and advisors should provide assistance to researchers in planning E&O activities, from proposal preparation through review and revision; promote submittal of proposals to agencies specifically for OOI/IODP-related E&O activities; and identify and foster partnerships, networks, and funding opportunities. One critical early partnership could be with one or more regional NSF-funded Centers for Ocean Science Education Excellence (COSEE), to start developing an organizational framework for a robust, top-down E&O presence in OOI/IODP. E&O staff and advisors should also help to assess critically the successes and disappointments in past activities, to make improvements going forward.

In the longer term, both the IODP and the OOI may wish to consider writing one or more proposals in response to future NSF Requests for Proposals for a thematic COSEE. An OOI/IODP thematic COSEE could be built around deep-ocean science in partnership with one or more regional COSEE program. Efforts should be made to explore additional partners for this thematic COSEE among universities, research institutions, other Earth Science programs, museums/ aquaria, industry, professional science and education organizations (e.g., American Geophysical Union, National Association of Geoscience Teachers), and media companies. It would be helpful to extract E&O content "nuggets" from OOI/IODP thematic science and technology priorities in the Initial Science Plan (ISP) and as proposals are submitted, and to look for content that is viable for development into E&O themes targeted at various audiences. Individual projects should be broken down into basic concept elements that may be used at the core of multiple efforts. Detail, science difficulty, and synergy with NSES can be added to address needs of more advanced groups (e.g., grades 5-8/public outreach vs. undergraduate/graduate curricular material vs. museum/aquaria) or to tailor the OOI/IODP message to specific groups (e.g., potential corporate funding partners, TV production companies).

Finally, we note that there are probably sufficient common needs within the OOI and the IODP, and a sufficiently high level of difficulty in fielding an an E&O effort as proposed herein, that there should be consideration of explicitly combining E&O efforts (personnel, office staff, activities, etc.) among the IODP and the OOI. We realize that this will be difficult at present because the OOI is not currently an international program, but (as discussed later), this may change in the future, and it would be wise to plan now for opportunities in economy of scale.

VI. Technical Discussions

Following introductory presentations and two sessions of thematic discussions and writing, workshop participants were divided into Technical Groups to assess needs for successful IODP and OOI research projects. Once again, group leaders were assigned to run these discussion sections, with a focus on technology (available, developmental, gleam-in-the-eye) that was essential for accomplishing fundamental goals of linked IODP and OOI projects. Workshop participants moved freely among the Technical Groups, and results of these discussions were presented and discussed among the workshop as a whole during the second day.

A. Pre/post survey, emplacement, and servicing (Technical group leaders: *Haymon, Underwood*)

This group focused on challenges associated with efforts involved in selection of sites, installation of long-term seafloor observatories, and maintenance and servicing of these systems. The overarching theme that emerged from these discussions was the recognition that establishment of the complete OOI (three kinds of observatory systems), in addition to a fully functional IODP (three kinds of platforms), will put a strain on available site survey and servicing assets. This problem was highlighted in the recent NRC report [*Detrick et al.*, 2003], in which it was noted that "[t]here are insufficient large global-class vessels and ROVs in academia to support ocean observatory installation and maintenance needs while continuing to meet ongoing expeditionary research requirements." For IODP-OOI to succeed, a renewed effort will be needed to maintain and expand availability of assets for exploration, site survey, and observatory servicing.

We recognize that neither the IODP nor the OOI is likely to be fully operational in all venues at the same time. Instead, these programs will grow in phases, with shifting priorities and areas of operation. There needs to be robust proposal and scientific pressure applied to the system in order to leverage additional assets and make the strongest possible case for the dedication of significant new resources.

Site survey needs will vary depending on the environment, site, and the specific experiments proposed, but in general, these elements may be required prior to establishment of subseafloor observatories: Surface ship bathymetry (multibeam and sidescan), magnetometer, gravimeter, multi-channel seismic, high-resolution sediment profiling, physical oceanography surveys (current profiling, CTD tows), reconnaissance sediment coring and heat flow. In many cases, further ROV or submersible investigation will be required to provide ground truth for geophysical observations, particularly where surface site-specific sensor arrays are also required. Some environments require that models be established and continually enhanced in order to place the initial and subsequent instrument arrays in the correct geometries and depth required to achieve the scientific aims of the project.

Site survey requirements for both the IODP and the OOI need to be kept flexible to accommodate the spectrum activities proposed. The spatial scale of experiments will dictate the survey requirements. For example, shallow observatories may need high-resolution seafloor and seismic surveys, whereas ultra-deep holes will require full 3-D MCS surveys. Additional needs may include: precisely navigated near- and on-bottom surveys/measurements, OBS refraction, electro-magnetics, seismic compliance, seafloor gravity, seafloor magnetics, Deep Tow seismics, OBS surface wave, water column surveys, camera surveys, and near-bottom sonar surveys.

Detailed surveys will be needed along cable routes to assess the operational needs of, and risks to, the observatory and also assess compatibility with other users (fishers, etc.); some cables may need to be buried. Safety issues also require communication between programs and careful records to ensure that deep submergence operations are not jeopardized by instruments or cables on the seafloor.

It is possible that both the OOI and the IODP will be able to contribute to the deployment of ROVs, HOVs, and AUVs, thereby augmenting international and UNOLS assets. For example, there is a need for additional deep-submergence (>3000 m), heavy-duty ROVs. OOI should explore opportunities for the use and adaptation of industrial ROVs and AUVs. The OOI may also wish to develop international partnerships for asset support, to facilitate the bringing of international ships and submergence vehicles to a wider community. The programs may also wish to develop international partnerships for asset support, to facilitate the bringing of international ships and submergence vehicles to a wider community. Similarly, survey activities might be leveraged by other oceanic observation programs (GOOS, IOOS, GCOS, satellite remote sensing, Navy programs, NOAA programs, other interagency efforts).

A final issue involves access to seafloor observatories and boreholes. As both programs develop and new components come online, there will inevitably be overlap in plans between users who wish to access the same seafloor facilities, sensors, samples, or data. For example, some experiments may require quiet, isolated conditions within a borehole, whereas others will require active perturbation of the environment. Who is to decide which objectives get priority for ship and borehole resources, and for how long? We anticipate some kind of joint IODP-OOI review panel for certain projects, and strong channels of communication must be crafted between programs (beyond the obvious panel liaisons). Some of these questions must be resolved as the ORION structure is developed over the next few years.

B. Sensors, Data Storage, and Retrieval (Technical group leaders: *Wheat, Chave, Chadwell*)

Topics discussed by this group included sensor requirements and availability, and issues associated with sensor and tool development. In addition, the group discussed storage, bandwidth, feedback and instrument control needs, and the nature of existing and planned developments. The group also discussed the potential benefits of defining generic tools (connectors, cables, adaptors) and the need for testing and calibration facilities. Many of these topics have been addressed at other recent meetings and workshops, but not necessarily with a focus on IODP-OOI linkages

Some critical sensors exist and others are being fabricated, but the scope and depth of various problems that scientists would like to address with joint OOI and IODP observatories currently cannot be fully accommodated with available instruments. It makes sense to pursue multiple development efforts simultaneously, and there needs to be a means for calibrating and comparing new and existing tools developed by different groups. Sensors must be operable across a wide range of conditions, including high temperature and corrosive environments. Sensors must be compatible with each other, with different observatory systems, and with multiple scientific objectives. There need to be mechanisms for establishing technical and performance standards and for resolving incompatibilities between sensors and measurements in these systems. These standards and requirements will need to be reviewed and updated on a regular basis, as the IODP and the OOI develop. Particular tools and capabilities of interest include seismometers, chemical and biological sensors, flow meters, tubing capable of avoiding contamination, and the ability to work at elevated pressures and temperatures. There is also a need for enhanced small-sensor (nano) technology. The group also discussed institutional barriers to technological development that are faced by many researchers. Designing, building, testing, and deploying new tools does not generally produce large numbers of publications or graduate students, and it can be deleterious to one’s career to dedicate too much time to such an effort. We will need to consider innovative means for encouraging these developments to go forward, including long-term funding, and support for development facilities. This community must also expand to incorporate engineers and scientists from other fields who can contribute to these efforts.

It would be ideal to design one or more standard interfaces for sensor attachment and for data access (for example by ROVs or AUVs). Similarly, consistent procedures for installing complex observatory instrumentation, cables, etc., need to be established and tested. At present, individual technical groups appear to be building their own interfaces to best suite immediate need(s). At one level, this is to be expected, because each scientific goal and experimental approach will demand particular physical specifications, computational capabilities, power, and data transfer rates. But if the development process is not guided towards common elements, there will soon develop technical and logistical conflicts and incompatibilities that will hinder scientific progress. Robust observatory standards must be established as part of the OOI and IODP.

With regard to data storage and retrieval, the working group was particularly concerned about data reliability and data. Whether observatory systems are cabled or autonomous, power and communications outages will occur, so data buffering and additional power storage may be required. Redundant systems also are necessary, as well as the ability to service systems on the seafloor to the greatest extent possible (as opposed to having to recover complete systems). Compatibility concerns should also guide considerations of docking and data transfer mechanisms, so that the same deep submergence assets can service many instruments. Once again, planning for this compatibility needs to occur as soon as possible, and should be repeated periodically as the programs develop.

C. Sampling and incubation (*Kastner, Fisk*)

The focus of this group was on recovery of fluid, gas, and biological material (rather than data), and on how to use these tools to facilitate in-situ experiments. The overall goal of these efforts is to accurately and comprehensively determine the biological and chemical properties of subseafloor environments on diurnal to decadal timescales. This overarching goal might be best met by a combination of sensors, autoanalyzers, and in-situ sampling at borehole observatories. As in-situ measurement technology and sampling technology evolve, their combined use in borehole observatories must also evolve. The greatest needs within this category of technology were considered to be (1) ship, ROV, and AUV facilities sufficient to support observatory time-series sampling, incubation requirements, and rapid event response; amd (2) long-term financial support for continued development, testing and deployment of sampling, incubation, and measurement technologies.

More specifically, there is a need to acquire and develop sampling tools capable of performing to these specifications: collect fluids, dissolved gases, and microorganisms with minimal contamination; regularly, at frequencies of hours to months; for relatively long durations (months to years); within multiple segregated intervals within boreholes; within the borehole from the seafloor; with both small-volume and large-volume samples; under both over-pressured and under-pressured conditions; in high-, intermediate-, and low temperature environments; in high-, intermediate- and low-pH environments; in high-, intermediate-, and low-salinity environments; without significantly altering the chemical and physical sample or environment. Opportunities for incubation experiments need to be available both in-situ and at the seafloor. There must also be opportunities for biological, chemical, and physical perturbation experiments under highly-controlled conditions.

The group discussed a classification system for technology availability, and came up with these categories and classifications.

- Available technology: CORKs, osmotic samplers (borehole and seafloor), seafloor (CORK outlet) discrete samplers. With regard to biological sampling for observatories, these tools are presently available: filter arrays, scavenging columns and exchange columns, flow-through cells for incubation.

- Developmental Technology: Advanced (multiple-horizon) CORKs, osmotic samplers with greater capabilities, flow-through cells for incubations, time-series discrete samplers for seafloor sampling, technology for borehole pumping tests (biological, hydrological, tracer). In-situ genome analyzers, mass spectrometers and other advanced technologies may also be possible within the next several years.

- Technology that is currently unavailable but is needed to achieve primary goals includes: Time-series discrete samplers within boreholes; high-pressure sample recovery and handling tools, high-temperature sample recovery and handling tools, and in-situ processing tools (filtration, fixation, extraction).

VII. Recommendations and Conclusions

Workshop participants discussed numerous common scientific and technical goals of the IODP and the OOI, as described in the preceding sections. The groups also identified several topics that will require attention as soon as possible so as to benefit from common interests, and to avoid having the IODP and the OOI working at cross purposes. Here we summarize the main recommendations from the workshop. Some of these are specific, technical or administrative suggestions, whereas others are more philosophical in nature.

Recommendation #1: Take advantage of common opportunities

IODP and OOI share numerous common goals and needs, including the development of sophisticated infrastructure for planning, operations, and technical development. Both programs are profoundly interdisciplinary, and will bring together scientists working in fields between which there has not been much collaboration in the past. Perhaps most importantly, both the IODP and the OOI are "exploratory" programs in the best sense of the term. The results of joint IODP/OOI experiments are going to be published in top-tier journals, will likely require revision to introductory textbooks in multiple disciplines, and will certainly excite the public at large with the wonder of scientific discovery. Maximum benefit from these common goals and needs can be achieved only if both programs coordinate carefully, share resources where possible, explore ways to leverage resources, and communicate freely as each program develops.

Recommendation #2: Internationalize ORION

The international nature of DSDP and ODP, and planned coordination among numerous countries within IODP, is profoundly important. There are similar programs to OOI (or ORION) being developed and led by other countries, including the gathering of site survey data, creation of new technology, and servicing of observatory systems. The exchange of information and personnel across international boundaries enhances the fundamental nature of scientific enquiry, speeds experimental design and execution, and brings a wider array of resources to address fundamental scientific problems. Workshop participants recommended that those involved in the OOI also seek to internationalize this effort so as to achieve these benefits, and to enhance joint operations during experiments of interest to both the IODP and the OOI.

Recommendation #3: Develop fully-integrated education and outreach programs

There has been a tendency within many Earth Science programs to treat E&O as an afterthought, and to separate the development of E&O activities from the fundamental scientific planning process. Both the IODP and the OOI are faced with a unique opportunity to integrate education and outreach (E&O) elements within all levels of planning and management of the IODP and OOI. Development of E&O capabilities within the two programs, including the support of dedicated, experienced staff with the right mixture of scientific, technical, and educational skills will greatly advance this area and counter a common misconception and a self-fulfilling prophecy: poorly-planned, inadequately-funded E&O efforts rarely succeed. E&O must be viewed as an investment that will generate substantial returns for scientists involved in the IODP and the OOI, and will help to generate continued (perhaps even increased) support over the 20-30 year lifetime of these programs.

Recommendation #4: Coordinate access to boreholes and other facilities

There are obvious economies of scale that can be exploited through coordination between programs. For example, research assets needed to emplace and service observatories might be developed or scheduled for use in a coordinated way, and engineering staff might be shared across programs, so as to transfer skills and technology. But there is also a fundamental need to coordinate system functionality and access. For example, a borehole observatory that is emplaced for a particular purpose (e.g., seismological monitoring) might also provide a valuable access point for another purpose (e.g., microbiological sampling). The greatest possible interdisciplinary benefit must be generated by each observatory emplacement, while not compromising the primary goals driving the science or jeopardizing experiments that are already underway. Who will decide which researchers have access to a particular installation following emplacement? How long will such priorities apply (one year? five years?). The current system operates largely on a *ad-hoc* basis, but this is likely to lead to conflict as both programs begin to address their primary objectives and the number and expertise of IODP and OOI investigators expands.

Recommendation #5: Recognize and plan for asset (platform, survey) needs

Full implementation of the IODP will involve simultaneous operations on multiple drilling platforms, and complete development of the OOI (including global, regional, and coastal components) will require ongoing use of a significant number of oceanographic vessels. Each individual experiment will likely require site surveys, and use of HOVs, ROVs, and/or AUVs for survey, emplacement, and maintenance is expected. Even if these technically challenging programs develop in stages over many years, the demands on existing research platforms and tools will be considerable. Anticipated needs should be recognized and quantified, and plans should be made to meet these requirements. In addition to assuring that the IODP and OOI are successful in achieving their primary goals, the maintenance and development of a broad array of survey and service assets will help to assure that effort directed towards the IODP and OOI do not detract from, or come into conflict with, fundamental research taking place around the world.

Recommendation #6: Accelerate development of essential sensors, samplers, connectors/interfaces and related technology

It has been recognized for sometime that observatory systems will require development, testing, and regular deployment of new generations of *in-situ* sensors, samplers, data storage devices, and related tools. There is currently no focused effort within the U.S. to develop, test, or maintain necessary tools – such developments are generally handled on an ad-hoc basis, with individual investigators writing proposals, building necessary development and testing facilities, etc. It should be recognized that tool development projects are <u>highly</u> risky; tend to require considerable trial-and-error testing; necessitate establishment of long-term, working relationships between designers, machinists, technicians, and scientists; and are often not amenable to student research, since they necessarily focus on immediate technical rather than scientific goals and require a long-term commitment. There should be some consideration of mechanisms that might be applied to help encourage and support technology developers as part of the IODP and the OOI, in stages ranging from design concept to technology transfer and maintenance.

Recommendation #7: Continue development of improved drilling, casing, and completion technologies

One lasting achievement of DSDP and ODP has been development of tools and methods for establishment of seafloor observatories, but considerable work remains to be done, particularly for observatories in bare-rock environments, and for establishing independent observational zones (depth intervals) in the subseafloor environment. Additional work is needed to develop tubing-in-casing technologies, and additional options for reentry cone deployment and removal. It is essential that there continues to be a focus on development and testing of these technologies and techniques, and that strong communication continue between scientific and drilling operations communities, to make sure that adequate preparation is made for future plans to establish borehole observatories. Similar efforts are needed to develop additional improvement to borehole observatory systems, including packers, pumps, plumbing, valves, and other components.

Recommendation #8: Reconsider the nature of "event response"

Particularly since the discovery of "event" plumes in the 1980's, scientists studying seafloor hydrothermal systems have recognized the importance of responding rapidly to sudden events. Scientists working in many fields understand the necessity of being able to respond to abrupt, dynamic behaviors within complex, natural systems (e.g., toxic algal blooms, atmospheric disturbances, seismic swarms, etc.). The approach in oceanography has generally been to wait for an event to occur, and then to mobilize rapidly for a somewhat "traditional" oceanographic expedition. As a practical matter, it has been difficult to respond to a large number of such events in a timely way, to keep assets available for use on short notice, and to get scientific, technical, and other personnel to shift schedules to accommodate response expeditions. Observatory science will allow a different kind of event response, one where observatory assets may be able to respond automatically to differing conditions, or where land-based control of observatory systems will allow changes to sampling frequency, injection of tracers, or other experimental components. There is a need for scientists involved in the IODP and the OOI to reconsider what "event response" might comprise as new observatories are added to a global network.

Recommendation #9: Integrate use of models, site surveys, and subseafloor observatories to develop and test hypotheses

There is much to be learned simply by passively monitoring natural processes in the subseafloor environment, but workshop participants are particularly intrigued by the possibility of developing and testing hypotheses through active experiments. New hypotheses will be developed through computer modeling of the subseafloor environment, and as a result of extensive site survey work that will be required in order to position these observatories. It will be essential to combine results of observatory experiments with modeling and surveying results so as to build a more complete picture of subseafloor environments and processes.

Recommendation #10: Support training of a new generation of scientists, engineers, and educators

Much as the IODP and the OOI will require considerable access to oceanographic assets such as ships and ROVs, developing and maintaining a global suite of observatory systems will require the dedicated effort of a new generation of scientists, engineers, and educators. Certainly these programs will create many opportunities for students and others at the early stages of their careers, but consideration should be given to attracting and retaining the brightest and most creative and energetic individuals. For example, the graduate fellowship program has been enormously successful the U.S. ODP community, and it may be worth considering whether such a program should be developed within the OOI. Such a program could include students working on observatory science, development of tools or systems, or education and outreach activities.

Recommendation #11: Don’t be afraid to think big, or to make incremental progress.

Both the IODP and the OOI are ambitious, visionary programs. They exist within today’s highly competitive funding environment, in large part, because those who participate in them have dared to dream of great achievements. The big questions that drove development of these programs must continue to set priorities for future activities. At the same time, participants at the workshop recognized that it will not be possible to launch all parts of these programs at the same time, and that it may require one or more decades for completion of individual projects. It would be a mistake to attempt development of a large number of complicated systems at the same time, particularly if there are practical limits to available ships, technology, and personnel (see earlier recommendations). Incremental progress is important, as it provides preliminary data and helps to drive technological development. Long-term success in both programs will require constant consideration of the big picture, and simultaneous recognition that our goals will be achieved one borehole, observatory, and node at a time.

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Appendix 2. Workshop agenda

Thursday, 17 July 2003, morning

Time	Person(s)	Topic
8:30-9:00	Fisher, Brown, Bertoldi	Welcoming remarks, logistics, presentation of agenda
9:00-9:20	Becker	Overview of IODP and the ISP planning process
9:20-9:40	Orcutt	Overview of OOI, planning process
9:40-10:00	Bohlen	Status of IODP funding, preparation, related programs
10:00-10:20	Isern	Status of OOI funding, preparation, related programs
10:20-10:40		*Coffee/drink break*
10:40-11:00	Delaney	Overview of technology, status and development
11:00-11:20	Gröschel, Robigou	Overview of Education and Outreach programs, needs
11:20-11:40	Fisher, Brown	Discussion of thematic group assignments, coverage, procedures for generation of text and figures
11:40-12:00	*Thematic groups*	Discuss draft outline, identify gaps, needs, procedures

Thursday, 17 July 2003, afternoon

Time	Person(s)	Topic
12:00-1:30		*Lunch – box lunches provided*
1:30-3:15	*Thematic groups*	Group discussions, assign writing responsibilities, begin writing
3:15-3:35		*Coffee/drink break*
3:35-4:00	*Thematic groups*	Prepare materials for presentation to full group
4:00-5:30	Full workshop	Short presentations from thematic groups, discussion
6:00-7:30		*Dinner*
7:30-		writing individually…

Friday, 18 July 2003, morning

Time	Person(s)	Topic
8:30-9:00	Fisher, Brown	Discuss workshop plan, review progress from preceding day, identify technical working groups
9:00-10:30	*Thematic groups*	Final meetings of thematic working groups, update documents, complete initial writing assignments
10:30-10:45		*Coffee/drink break*
10:45-11:15	Full workshop	Reconvene full workshop, overview of goals for technical working groups
11:00-12:00	*Technical groups*	Initial technical group discussions of needs, issues to be addressed, writing responsibilities

Friday, 18 July 2003, afternoon

Time	Person(s)	Topic
12:00-1:30		*Lunch –many local options*
1:30-3:15	*Thematic groups*	Technical group discussions, writing
3:15-3:35		*Coffee/drink break*
3:35-4:00	*Thematic groups*	Prepare materials for presentation to full group
4:00-5:30	Full workshop	Short presentations from technical groups, discussion
5:30	Full workshop	wrap-up, workshop ends

Appendix 3. Workshop abstracts (proposed new “experiments”)

The following abstracts were submitted by workshop applicants in response to this request at the application web site:

“Participation at this workshop may be limited, depending on the number of applications and availability of meeting facilities, etc. In the boxes below, please enter title, authorship, and text for a one-page abstract describing a new experiment that could be accomplished as part of a joint IODP and OOI effort. The focus should be on the kind of science that could be done through the IODP and the OOI, not on specific locations where these experiments might occur. The ideal experiment will take advantage of unique opportunities provided by the IODP and the OOI, and move the science forward in a way that is not possible without one or both of these programs.

Abstracts will be read by the conveners and used to help select Workshop participants. Abstracts will be used to help craft the draft report outline, and to define the range of scientific topics and technical needs discussed by the Workshop participants. In addition, a book of abstracts will be distributed in advance to workshop participants, and may be included as an appendix to the Workshop report. Please limit your abstract text to 250 words.”

CORK hydrogeological observatories in the Integrated Ocean Drilling Program

Keir Becker and Earl E. Davis

The success of ODP CORK sealed-hole hydrogeological observatories since the early 1990's was a prominent thread in the development of the Ocean Observatories Initiative. CORKs represent one of the two main borehole observatory types (the other being ION/OSN seismic observatories) that directly linked ODP to early seafloor observatory initiatives, and there is considerable opportunity for developing these linkages even further when IODP and the OOI commence this decade.

Deep-sea microscopy: In situ exploration of life in extreme environments

Samuel S. Bowser and Joan M. Bernhard

Our aim is to develop microscopy equipment for studying micro-, meio- and macrobiota inhabiting deep-sea settings. The smaller benthic fauna of the deep sea strongly influence biological as well as geochemical processes, including certain extreme environments (e.g., seeps, basins). The microscope will serve as both a primary observational tool and a targeting aid for micromanipulation of accessory analytical probes. Instrument development will focus on adapting off-the-shelf optical and digital image technology.

Seafloor geodetic component of IDOP-OOI

C. David Chadwell

Measuring and interpreting the present-day crustal deformation of the seafloor is a new area of investigation and its development is quite young compared to the other approaches for monitoring seafloor. Deformation is defined in the usual sense as the change in the spatial relationship between surface markers, usually artificial, between two points in time. This change in spatial relationship is usually resolved into a horizontal component and a vertical component. Several techniques are emerging to measure both the vertical and horizontal components of deformation with centimeter resolution. Seafloor deformation is associated with the magmatic and tectonic processes that create crust at ocean spreading centers, transport it across plate interiors and subduct it at trenches. By observing deformation at the sea floor, inferences can be made about underlying processes, complimenting interpretations based upon seismic, hydrothermal and data derived from drill hole studies. Seafloor geodesy provides the opportunity to monitor crustal deformation across the entire life-cycle of a plate from creation to subduction. Because deformation measurements must be collected over a time series long enough to encompass earth movement, seafloor geodetic approaches benefit from observatory infrastructure. Drilling efforts, particulary in subduction zones, could benefit from long-term, in-situ monitoring of seafloor deformation, for example, seismogenic zone invesitgation of the onset of thrust fault locking. My contribution would be to discuss how these techniques can be incorporated and benefit the IDOP-OOI effort.

HOBO: Hawaii-2 Ocean Borehole Observatory

Alan Chave, Frank Vernon, John Orcutt, Ralph Stephen

HOBO builds on the results of the OSN Pilot Experiment and covers the 2004 installation and validation of the first operational borehole seismic installation in the deep ocean. During ODP Leg 200 in December 2001, a cased re-entry borehole was drilled near the Hawaii-2 Observatory (H2O) site (about 28°N, 143°W, or halfway between California and Hawaii) expressly for the installation of a seismic sensor. The H2O site incorporates a seafloor junction box which provides power and real-time, two-way communications to Hawaii via an abandoned submarine telephone cable. The OSNPE seismic sonde is being modified to bring it up to GSN standards. A method and apparatus to lay a fiber optic cable ,extension cord, from a deep submergence ROV over multiple km distances is being developed, as the borehole is located about 1.5 km away from the H2O junction box. HOBO will culminate in the installation of the borehole seismometer and its connection to H2O. Installation of a thermistor string in a nearby uncased hole is also planned. The data from HOBO will be freely available over the world-wide web through the IRIS Data Management Center, just as for any terrestrial GSN station, and over the Internet through an object ring buffer. HOBO serves as an early component of a larger ocean observatory infrastructure that has received national endorsement and is being actively pursued by both the coastal and deepwater oceanographic communities.

Transience and Earthquakes

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Fundamental questions continue to be asked of subduction zone environments and it is clear that active tectonics, hydrology and perhaps even geochemistry are all involved in determining their behavior. Many different issues can be examined with a regional scale observatory network that includes geodetic measurements, seismicity studies, monitoring of hydrological processes (flow, pore pressure, chemistry) and strain both at the surface and in the subsurface (i.e. in boreholes). For example, the coseismic and subsequent viscoelastic slip from one large earthquake is thought to regionally transfer stress that loads the fluids and rocks of the surrounding plate boundary directly triggering or accelerating the occurrence of subsequent destructive earthquakes. Temporal clustering of large regional events has been noted in a number of regions including north Anatolian fault, eastern Mediterranean, Iran and Mongolia and the San Andreas. In subduction environments, the Nankai system has the longest historical record of large devastating earthquakes that appear to often occur as characteristic doublets. The suggestion is that stress increases of a little as 0.1 to 1 bar and the associated time dependent poroelastic effects can trigger or accelerate subsequent events on nearby unruptured sections of a plate boundary and that such stress triggering can occur over scale lengths of >50km to perhaps as much as 400km (and perhaps over plate scales between different plate boundaries). Indeed, the associated plastic/elastic volumetric strains and and subsequent decay of induced pore pressure perturbations may determine the temporal decay and spatial patterns of the aftershocks to distances >50km from larger ruptures.

Very recently there has also been a acceleration in the identification of slow/silent earthquakes events in subduction systems. Subduction systems because of their low angle tend to have a relatively broad down dip seismogenic zonation with the portion releasing seismic moment being sandwiched between upper and lower aseimic zones. To date most silent earthquakes that have been identified occur in the deeper aseismic region that lies beneath land. It has previously not been possible to track slow silent earthquakes offshore but we have that chance now. Perhaps the shallower subduction system also episodically creeps destabilizing the upper seismogenic region. Slow silent rupture may in fact explain the long standing indications of a discrepancy between total (plate motion-related) moment and the lower values of the seismic moment summations and be a common phenomena in subduction zones. It is also likely that slow silent earthquakes can be triggered by or can trigger the more dangerous moderately fast tsunamogenic or fast seismic events. These and many other topics would be ideal areas of study utilizing multiple long term (cable and buoy) surface and borehole observatories and a variety of interdisciplinary measurements techniques at suitable sites distributed along active plate boundaries.

Potential microbial biomass and activity in off-axis ocean crustal fluids

J. P. Cowen, S. Giovannoni, F. Kenig, and C. Taylor

We are interested in continuing our studies of the potential for and characterization of microbial growth in crustal fluids circulating in off-axis crusts. We have successfully utilized the fluid delivery capabilities of the ODP's CORK observatory system at the overpressured borehole 1026B (Cowen et al., 2003, Science 299, 120-123). There remain tremendous advantages to the existing CORK systems in terms of fluid sampling. Nevertheless, the next generation of CORK observatories will hopefully offer new opportunities for fluid sampling/experiments. This next generation of CORKs is being designed now and in the near future. They should include, as much as possible, the sampling requirements of microbial geochemical studies; for example: fluid sampling from compartmentalized vertical sections of the upper crust (multi-packer experiments), improved materials used in fluid delivery systems, and down hole in situ experimentation.

A plate-scale borehole monitoring experiment to study the links between hydrogeology and seismotectonics

Earl E. Davis and Keir Becker

Regional crustal strain resulting from seismic and aseismic slip has been observed in several instances via borehole pressure monitoring. Examples include strike-slip and extensional plate boundary events on the Nootka transform fault and the Juan de Fuca Ridge, and intra-slab events in the Mariana subduction zone. Strain is well resolved in pressure at locations up to 250 km away from the locations of slip. The hydrologic response includes elastic (instantaneous) and hydrologic (diffusional) contributions, and possibly one from viscoelastic deformation. The spatial pattern of elastic deformation provides a valuable constraint on seismic efficiency (in some instances where no coherent seismic energy is generated it provides the only constraint on slip) and the hydrologic response provides a valuable constraint on the large-scale hydrologic properties of the formation (which have been observed to vary with the state of stress). To date, observations have been made in holes drilled originally for other purposes; future studies should improve upon this situation.

The northern Juan de Fuca plate provides a unique opportunity to establish a suite of monitoring sites specifically designed for the purpose of hydrotectonic monitoring. Factors that contribute to this uniqueness are:

1. The scale of the system. Coherent signals can be seen from slip events equivalent to moment magnitude between 6 and 7 over the full width of the plate. Thus it is possible to obtain data that are spatially unaliased.
2. Frequency of occurrence. Events of this magnitude occur frequently along the Juan de Fuca Ridge (low-efficiency spreading events), the Nootka Transform fault (strike-slip events), and the Cascadia subduction zone (high-efficiency slab events, and very-low-efficiency silent-slip subduction thrust events) (c. 1 yr-1 each).
3. Thick sediment. The thick and continuous sediment layer of sediment over this region slows hydrologic drainage and allows proper resolution of slow strain accumulation before the pressure transients dissipate.
4. NEPTUNE. If the planned NEPTUNE fiber-optic network becomes reality, a suite of borehole observatories could be provided with power and a data link to shore. This would allow service-free observations over multiple decades, and sampling rates that could provide quantitative overlap between seismic and geodynamic observations.

With these opportunities in mind, planning needs to begin so that an optimal array of holes is established, and so that multiple objectives can be met at each of the sites (e.g., accretionary prism growth, fluid expulsion, and gas hydrate objectives along the Cascadia margin, ocean crustal hydrologic, geochemical, and microbiological objectives at ridge flank sites, and hydrothermal objectives at axial sites). Planning also needs to begin so that optimal engineering design can be achieved to streamline drilling and installation operations.

A Long-term Monitoring Experiment for Study of Life in Ocean Crust

Steven D'Hondt and Brian Heikes

The study of life in deeply buried ocean crust would be critically aided by long-term monitoring of CORKed boreholes. Drilling of ocean crust can be expected to severely perturb the biological communities of crust in the borehole vicinity. As the physical and chemical conditions of CORKed ocean-crust boreholes evolve toward crustal conditions from open-hole conditions, the biological communities and activities in the CORked holes presumably also change. Under ideal circumstances, as the physical and chemical environment stabilized in individually segregated intervals of a CORKed hole, the biological communities might grow to closely resemble native crustal communities. Factors that are likely to influence successions of communities and activities within the CORKed hole include (1) evolution of the chemical and physical environment within the hole, and (2) removal and introduction of cells by hydrologic flow within the ocean crust. The evolution of the environment and the succession of biological communities throughout the transition from an open hole to an environmentally stable CORKed hole can be directly documented by long-term chemical, biological and physical monitoring of physically isolated intervals of CORKed boreholes. This monitoring might be most effectively done by integrating CORKed IODP drillholes with downhole AAA (autoanalyzer-autosensor-autosampler) packages into broader Ocean Observatory systems. Properties of particular interest for such long-term monitoring include the chemical and physical characteristics of the CORKed environment, chemical signatures of net metabolic interactions, rates of in situ activities, genetic evidence of the organisms present in the environment, and direct evidence of the organisms active in the environment.

In-situ pH measurement of hydrothermal fluids at Mid-ocean ridges

Kang Ding, William E. Seyfried Jr., Margaret K. Tivey, Karen L. Von Damm, Albert M. Bradley, and Zhong Zhang

The in situ pH measurements of seafloor vent fluids were conducted using a newly developed solid-state sensor. Measurements were made during a series of dives with DSV Alvin at the Main Endeavour Field, MEF, Juan de Fuca Ridge, 9 East Pacific Rise, EPR, at 21 BAN, EPR at 9-10 BAN, and at the Galapagos Rift. Vent fluid temperatures and pressures ranged from 22 to 380 C and 220 to 250 bars, 2200 to 2500 meters depth, respectively. The pH of the highest temperature fluid is only slightly acidic, 85.1-5.4, instead of being at least a full unit lower as often measured at the room condition from fluid sample. However, our in-situ pH results are at the same magnitude with theoretically predicted in-situ values from the room condition measurement. Dramatic pH lowering is observed during vent fluid mixing with seawater, which is likely due to the effect of cooling on metal sulfide precipitation and homogeneous equilibria. In contrast, pH of low temperature diffuse flow vent fluids at Galapagos decreases with increasing temperature achieving values approximately 0.5 units lower than ambient seawater at the discharge point, where the fluids are 2 C and directly associated with colonies of Riftia pachyptila. The ability to measure and monitor in-situ pH in real time offers great promise for future study as efforts continue to better understand the complex interplay between inorganic and organic processes associated with hydrothermal activity at mid-ocean ridges. By accessing IODP facility, we expect that the application of this in-situ chemical sensor along with the others could be greatly enhanced, especially considering the opportunity to combine the sensor deployment with the drilling activity.

Three-dimensional measurements of seafloor shear velocities

LeRoy M. Dorman, Allan W. Sauter

The deep-ocean and regional-scale observatories will be the focus of detailed experiments measuring fluid flow, heat flow and sediment transport. Many of these can benefit from knowledge of more physical properties of the seafloor than are usually available. Specifically we propose to measure the shear velocity of the upper few tens of meters of seafloor materials. Newly-developed shear wave generators which can operate on the sea floor do not use explosives and are thus environment-friendly. Measurements of the dispersion of Scholte waves over path lengths of 100-1000 meters provide shear velocity as a function of depth. These path integrals can be combined to yield areal
coverage.

The signals observed are typically dominated by a fundamental-mode wave train terminated by a prominent Airy phase. These group velocity of the Airy phase is approximately the surficial shear velocity. The values of shear velocity observed can be as low as 16 m/s. Sediments with shear velocities this low are not usually recovered by sampling techniques because of the ""soupiness"" of the material.

Scholte waves are dominantly P-SV waves. We believe that the possibility exists to measure Love (SH) waves as well. The combination of the two types of propagation provides identification of sediment anisotropy and should offer clues to the means of deposition and compaction.

Re-use of Retired Submarine Telecommunications Cables for Ocean Observatories

Fred K. Duennebier and Rhett Butler

Early retirement of the first and second-generation submarine optical telecommunications cable systems provides an extraordinary opportunity for ocean observatory science. These systems, installed across the oceans between 1989 and 1995, could provide continuous high-bandwidth, high-power infrastructure for more than 12 observatory nodes on each cable. The possibility of such “strings of pearls” stretching thousands of km across the ocean floor changes the assumptions on what is possible and practical for ocean observing systems.

Enough cable is being retired in the Pacific basin alone within the next few years to go around the world. These cables all operate at a maximum of about 8 kVDC with a current of 1.6 amps, with two operating fiber pairs. Each fiber pair in the first-generation systems operates at 280 Mb/s, and at twice that rate in the second-generation systems. While several of these cables are in locations of considerable scientific interest where they are, others might be best utilized by moving a portion of the cable (still using the same cable station) or by removing part of the cable for re-use in a completely new location. The high performance reliability of these systems suggests that they should be operational for at least the next 20 years.

As these systems are retired (several of them this year) the telecommunications industry will dispose of much of the equipment and spares that will be needed to efficiently utilize these cables for observatories. Efforts are underway to insure that as much of this equipment is saved for future use.

Cross-hole hydrologic experiments in oceanic crust: determining the distribution of hydrothermal flow paths at a crustal-scale

A. T. Fisher and the proponents of IODP Proposal 545Full3 (please see: http://www.isas-office.jp/active.html#list)

We have proposed a multidisciplinary project to evaluate formation-scale hydrogeologic properties (transmission, storage) within oceanic crust; determine how fluid pathways are distributed within an active hydrothermal system; establish linkages between fluid circulation, alteration, and geomicrobial processes, and determine relations between seismic and hydrologic anisotropy. We will accomplish these goals on the eastern flank of the Juan de Fuca Ridge, through use of two existing borehole observatories penetrating uppermost crust, ODP Holes 1026B and 1027C, and through drilling two new holes (600 m and 200 m into the crust) that will be cored, sampled, instrumented, and sealed. We will conduct the first controlled, multi-dimensional, cross-hole experiments attempted in the oceanic crust, including hydrologic, microbiological, seismic, and tracer components.

After completion of drill-ship operations, we will initiate a series of multi-year tests using this network of subseafloor observatories, allowing us to examine a much larger volume of the crustal aquifer system than has been tested previously. By monitoring, sampling, and testing within multiple depth intervals, we can evaluate the extent to which oceanic crust is connected vertically and horizontally; the influence of these connections on fluid, solute, heat, and microbiological processes; and the importance of scaling on hydrologic properties. We propose to complete this work where (1) thick sediment cover isolates permeable basement, allowing small pressure transients to travel long lateral distances, (2) outstanding coverage of seismic, heat flow, coring, geochemical, and observatory data allow detailed hypotheses to be posed and tested, (3) existing ODP drill holes and long-term observatories provide critical monitoring points for pre- and post-drilling experiments, (4) the formation is naturally overpressured so as to drive multi-year, cross-hole experiments (5) and a cabled seafloor observatory network may facilitate long-term experiments, data access, and instrument control. This work will elucidate the nature of permeable pathways in the crust, the depth extent of circulation, the importance of permeability anisotropy, and the significance of hydrogeologic barriers in the crust. We will learn where viable microbiological communities live, and how these communities cycle carbon, alter rocks, and are influenced by flow paths. We will quantify lateral scales over which solute transport occurs, the extent of flow channeling and mixing in the crust, and how these processes relate to rock structure and fabric. We will determine how to relate seismic velocities and velocity anisotropy to hydrogeologic properties.

Much of this work can be completed with currently-available technology, but the establishment of a networked observatory system that includes these drilling sites would allow real-time monitoring of thermal, pressure, and chemical conditions; modification of pumping and sampling rates; and long-term injection of tracers that will help to resolve the nature of fluid pathways in the crust. This would represent a major advance in determining how coupled fluid-heat-solute-biological transport and reaction occur in the seafloor.

Ocean Crust In Situ Microbial Activity

Martin Fisk

In much of the literature on the subject of microbes in the igneous ocean crust it has been assumed that the crust supports microbial communities. Although there is compelling evidence that the crust supports a subsurface biosphere, this has not been explicitly demonstrated. We plan to use short-term (days) and long-term (months) in situ incubations in flow-cells open to borehole water to evaluate this hypothesis. The in situ incubations eliminate the problem of duplicating in the lab the temperature, pressure, and fluid composition of the borehole. We also plan to use single-well, "push-pull" tests to determine in situ rate of microbial metabolic activity.

CO_2 sequestration in subseafloor basalt aquifers

David Goldberg, Juerg Matter, Taro Takahashi

The long-term sequestration of CO_2 in a deep saline aquifer within the oceanic crust may offer a technically feasible means of reducing atmospheric build-up of this greenhouse gas. The objective of our research is to identify and characterize appropriate sites with large capacities for the injection of CO_2 and subsequently monitor hydrogeological and geochemical processes for secure containment of the aquifer and retention of carbon over long periods of time.We envision multi-hole drilling at moderate water depths (~2500 m) and new observatory installations to address fundamental questions concerning the potential injection of CO_2 and its subsequent immobilization as non-toxic and stable Ca-Mg carbonate crystals in fractured oceanic basalt. Complex drilling plans and new CORK-type instrumentation to monitor hydrogeological (hydraulic conductivity, fluid pressure) and geochemical (temperature, pH, electrical conductivity), parameters as well as sampling of interstitial fluids for geochemical analysis will be required. Real-time monitoring of these data is not essential for the initial experiments but would be critical for long-term monitoring of an active sequestration site.

Implementation Strategies for an Education and Outreach Component of the Ocean Observatories Initiative

H. Gröschel, V. Robigou, S. Jagoda, D. Randle, and P. Coble

The Education and Outreach (E&O) session at the IODP/ OOI Workshop will focus on the most effective ways to promote the sciences and technologies related to ocean drilling and deep-sea and coastal observatories to the public, students, teachers, and the greater science community. A key goal is to communicate the excitement of exploring the oceans via the unique, cooperative, international research programs of the IODP and OOI.

The E&O group is comprised of a high-school teacher, a science educator– curriculum developer, and three research scientists with E&O experience. The last four attended a May 2003 IODP Education workshop, and encourage the OOI to share ideas, resources, and opportunities to develop recommendations for innovative and realistic research-based education and outreach programs.

Topics for discussion will include:

(1) What are the target interest groups for IODP/OOI E&O: K-4, 5-8, 9-12, undergraduate-graduate, informal-public education? Need to prioritize effort.

(2) What themes will resonate with these groups? Earthquakes and plate dynamics? Earth history? Undersea volcanoes and life? The deep biosphere? Visualization technology?

(3) How will target groups benefit from interaction with IODP/OOI and vice versa?

(4) What is required for improved communication between information suppliers (researchers, program directors), translators (science & informal educators, teachers), and consumers (teachers, students, public)? What about federal and state educational standards and assessment criteria?

(5) What are the most effective product/implementation strategies and for what audience? (Web-based, TV, print, CDs, museum exhibits, “real-time” communication with ship, modular commercial educational packages, teachers at sea)

(6) Are other partnerships a good idea for IODP/OOI? (NEPTUNE, COSEE, NMEA, NSEA, universities, private sector, government agencies)

Documenting and Monitoring Temperature Variations in Oceanic Bottom Water with CORKs

Robert N. Harris

Knowledge of bottom water temperature (BWT) variations is important to understanding the vigor and nature of ocean circulation as well as the nature of climatic interactions between the ocean and atmosphere. The biggest obstacles to understanding variability in bottom water are: 1) the lack of an observational network, and 2) historical data that are too short in time and too sparse in space. I propose to investigate the feasibility of reconstructing BWT histories at the decade to centennial time scale by making high-precision temperature-depth measurements. Because marine sediments have a low thermal diffusivity, variations in BWT propagate slowly downward perturbing the background thermal field. These temperature anomalies are a direct thermophysical consequence of a changing BWT condition, and will be used to reconstruct BWT histories. A conductive thermal environment is necessary for this experiment. This can be ensured by locating a hole is low permeability sediments and isolating a thermistor string between a borehole seal or CORK (circulation obviation retrofit kit) at the top of the borehole and a packer below the thermistor string. A sensitivity analysis using observed BWT variations from the North Atlantic indicates that a signal is present and resolvable. By measuring thermal transients as a function of time at such a borehole observatory the transient component of BWT variation can be directly observed and compared to measured variations in BWT. The possibility of reconstructing BWT histories with sufficient resolution creates the potential for transects of such measurements across climatologically important gateways.

Technology for Drilling the Crest of an Unsedimented Fast-Spreading Ridge and Instrumenting Boreholes for Integrated Studies of Ridge Crest Processes

Rachel M. Haymon and ten other proponents of an IODP proposal to drill the EPR at 9N

We are revising the EPR 9N drilling proposal this summer, and I want to develop ideas for the proposal and discuss development of useful technology that we might propose to use.

Crustal Aging and fluid fluxes; Emphasis on 0-20 Myrs

Miriam Kastner

In order to understand the processes of crustal aging while fluid flow is more intensive and sediment cover <30-200m, a three-leg program is proposed. Drilling ridge-flank transects through the sediment cover and into oceanic basement, 100-150m, from 0.001-20myrs crustal age, at a very fast, medium and slow rates of spreading, is proposed. This will provide information on the aging of the oceanic basement alteration of the sediment column, and chemical and isotopic fluxes through outcrops versus through sediments, from the time fluid flow is through both basement outcrops and sediment cover to when flow through sediment ceases. This will require an interdisciplinary team, the research will involve seismology, heat flow, tectonics, sedimentology, hydrology, geochemistry, and rock physics. At least two of the transects will be in the eastern Pacific. At the very young crust zero to 6myrs) portion of the sections sites (at least 2 each) should be located at 1-2 myrs interval and at the 'older' sites at intervals of 3-4myrs. This proposal could be integrated with the one proposed by John Sclater et al., extending the study to older crustal ages.

Mapping and monitoring seafloor activities associated with seismogenesis at plate convergent boundaries through integrated use of seafloor cables and deep boreholes

Masataka Kinoshita, Wonn Soh, Juichiro Ashi, Harold Tobin, Masanao Shinohara

Detailed mapping and long term monitoring are the keys for the detection of present and past activity of seismogenic faults at plate convergent boundaries. Mapping of the seafloor will clarify the dynamics of active processes at plate margins in a more precise way than on land, if it can be made with much better navigation accuracy than can be achieved today. We start with a deep-tow mapping with conventional navigation tools in the Nankai accretionary complex, which is a target for the IODP drilling into the seismogenic zone. Next we plan to develop an AUV system in the same region within 5 years. Also, the "Navigable Sampling System" is now under construction for accurate sampling of the sediment using a precise navigation and a video camera. Simultaneous measurement at seafloor and boreholes is essential to know how the plate convergence deformation is accommodated within the accretionary complex, and to know how the stess in time and space. Long-term monitoring of strain, seismogenic faults is proposed in an IODP proposal at Nankai. Seafloor geodetic measurement using acoustic GPS techniques is under development by some groups in Japan. In order to improve the accuracy, seafloor cables will make a significant contribution. Seafloor cables, if connected to the borehole observatories, could be a useful tool for the prevention of potential eathquake and tsunami disasters.

Hydrate Research at the USGS

Dawn Lavoie, Deborah Hutchinson, Tim Collett

The long-term goal of the USGS gas hydrates effort is to understand and model the processes controlling gas-hydrate formation and occurrence from local to global scales in order to accurately assess the energy resource potential of offshore gas hydrates, hazards related to seafloor stability, and the potential environmental impact of hydrates on global climate change. Use of the IODP drilling platform would allow scientists to investigate drill core property changes relative to the effects of acquisition, recovery and storage of hydrates, and evaluate the effects of borehole drilling on downhole measurement systems. To assess the role of gas hydrate on sea floor stability, USGS scientists want to (1) provide input to geologic and engineering models on drilling through gas hydrate by analyzing the physical properties of hydrate/sediment mixtures over a range of grain sizes and hydrate saturations, examine the microfabric of drill cores using scanning electron microscopy, and characterize the hydrates geochemically, and (2) develop/refine models for the quantification and characterization of hydrate in sediment using seismic data, and calibrate models using data from relevant laboratory experiments. In order to assess the role of gas hydrates in global climate change, USGS scientists want to understand the distribution of gas hydrates in nature through field programs. IODP can provide deep cores otherwise unavailable. Analyses of IODP cores can help us understand the processes that control natural distribution, the conditions that result in the release or sequestration of hydrates in the global reservoir. The question to be answered is "are hydrates an important factor in climate change?

Development and application of long-term stationary observation system at the deep seafloor

Kyohiko Mitsuzawa

To understand the long-term phenomena in the deep sea areas related to deep current, hydrothermal activities and seismic activities, it is effective to observe using multiple instruments at a fixed location. For this purpose, we have been developing stationary seafloor observatories such as a self-memorized observatory and a real-time cabled observatory. The self-memorized observatory developed to observe the hydrothermal activities as areas in the North Fiji Basin, Mid-Atlantic Ridge, Southern East Pacific Rise and Western Pacific. It basically consists of a deep sea still camera and strobe, current meter, CTD, nephelometer and 8mm underwater video camera system. The real-time cabled observatory developed to observe the seismic activities and deep sea environmental phenomena including deep currents in the subduction zone around Japan. It consists of seismometers, video camera, CTD, ADCP etc. Through the various observations, we confirmed that the tidal effect was a strong factor for forming the hydrothermal plume and enviornmental changes in the hydrothermally active　area. In the Japan Trench and the Nankai Trough, the strong deep currents were found to circulate along the trench slop as a boundary current.

We would like to maintain the deployed observation systems and to develop a new observation system which related to IODP and NEPTUNE.

Monitoring microseismicity

Mladen R. Nedimovic, D. Wayne, R. Bohnenstiehl and Suzanne M. Carbotte

High-quality 2D multichannel seismic reflection data collected in July- August 2002 during the NFS funded EW0207 cruise are currently being processed at Lamont, Woods Hole and Scripps institutions. The first finalized reflection sections (1, 3 and 17) at the Lamont-Doherty Earth Observatory approximately follow the corridor outlined by the newly proposed drill hole sites for the IODP Proposal 545 (Fisher, A. T. et al., 2003). Observations on reflection images. At several places, reflection sections clearly show faulting within the sediments and the shallow basement. Fault offsets gradually diminish upsection with sediment age, from older to younger, which suggests growth faulting caused by long-term slip within the basement structure. The faults do not appear to break the topmost sediments indicating a very slow faulting process or lack of current tectonic activity. Folding due to compaction at places where there are large offsets in the basement structure, and faulting in the sediments where there are only small offsets in the basement further suggest both: (1) that the sediment rupture is not caused by compaction but rather by steady movements in the basement that produces growth faults; and (2) that the faulting does not necessarily occur at the pre-existing planes of weakness formed at the Jaun de Fuca ridge.

The main fault zone covers the area between the proposed Deep Ridge (DR) and Second Ridge (SR) drill sites. Largest fault offsets are found in the middle of this ~30 km wide area. Several faults within the sediments are also visible at ~40 km west from the SR drill sites and ~23 km east of the First Ridge (FR) drill sites. Deep and steep crustal reflection events in this area most likely outline faults that cut through the oceanic crust and appear to extend from the faults within the sediments to the anomalously bright Moho. Ridge flanks are generally considered to be tectonically stable and the origin of the imaged normal faulting is not well understood. The Juan de Fuca trench is only about 100 km east from the main fault area and bending of the oceanic slab due to subduction is a likely driving force for the observed faulting. However, this force cannot be large because plate bending in warm subduction zones such as Cascadia is gentle. The faulting is not continuous along the ridge flank and its magnitude does not monotonously decrease away from the trench, as would be expected from pure slab bending, indicating other factors in the faulting process. Magnetic and bathymetry data tie the two fault areas to propagator wakes. The oceanic crust formed at ridge propagators may be weaker than the oceanic crust formed at ridges, and could thus represent a zone of preexisting weakness first to be faulted. The obliqueness of the subduction zone may also result in anomalous stress and strain distribution within the approaching Juan de Fuca plate.

Proposal for monitoring microseismicity.
Location, magnitude and source mechanism of local microseismicity, in combination with available high-quality reflection, magnetic, gravity and bathymetry data, is essential for in-depth understanding of the origin, geometry and current activity of the observed faulting on the eastern Juan de Fuca ridge flank. A more complete understanding of the faulting, at both small and large scale, would lead to a better understanding of crustal evolution and the nature of fluid flow at buried ridge flanks. Although numerous experiments done or planned at the ODP and newly proposed IODP drill sites have and will provide a great wealth of geologic and hydrogeologic

information, they cover only a small area and do not provide information on fluid flow below the extrusive layer 2A.

New reflection data (ew0207 cruise) show that faulting can extend all the way through the sediments and crust to the Moho. Strong reflections within isotropic and layered crustal gabbros are not likely unless the rocks are serpentinized at fault planes, which is indicative of fluid flow deep into the crust. Anomalously bright Moho observed where the deep faults plunge into the upper lithospheric mantle suggests that fluid exchange may extend much deeper than generally thought. The IODP experiments also may be biased when done within anomalous crust formed at ridge propagators. Hydrophones of the SOund SUrveillance System (SOSUS) currently are capable of detecting only moderate-size earthquakes (magnitude 2.5 to 3 and greater) in the study area. Seismometers placed in existing drill holes, or planned for new IODP drill holes, can record local microseismicity but the density of instruments is insufficient for accurate determination of hypocenters or source mechanisms. Therefore, it would be of great value to monitor microseismicity at three study areas: 1) At the main fault zone between the proposed DR and SR drill sites; 2) At the fault zone between proposed SR and FR drill sites, where the faults in the sediments appear to connect to deep faults that extend all the way to the Moho; 3) At the Juan de Fuca ridge some tens of kilometers to the west. The optimal time to run this experiment (9-12 months) is during the proposed IODP drilling and/or during subsequent long-term seafloor pump testing powered by cable, when changes in pore fluid pressure may result in increased microseismicity within these fault zones. Ideally, three groups of 8 to 12 ocean bottom seismometers (OBS) would be placed at the seafloor. Each OBS group would form a pre-designed pattern to allow for monitoring of microseismicity throughout the sedimentary and crustal sections within an area with a diameter of 5-10 km. The first group of OBSs is planned to continuously monitor the processes near the Juan de Fuca ridge axis within the Endeavor Integrated Study Site, where significant magmatic and tectonic perturbations are expected. The second and third groups of OBSs would be placed in the main fault zone area (between the SR and DR holes) and in the area of the large crustal faulting (between the FR and SR holes). Placing the third group of OBSs between FR and SR holes may be of particular value because faulting in this area cuts across the whole crust and the sediments. To carry out this part of the experiment one of the FR drill sites needs to be moved about 23 km east and long-term seafloor pumping powered by cable has to done at this new drill site.

The proposed experiment will make use of natural and induced microseismicity to accomplish the following goals: 1) To determine if the observed growth faults in the sediments are currently active; 2) To determine if the deep faults that cut the crystalline crust are active; 3) To study the connection between the sediment rupture and deep crustal faults; 4) To obtain additional information about the fault distribution, geometry and fault mechanism; 5) To examine how pore fluid pressure changes induced by pump-tests influence the rate of microseismic activity within the fault zones; 6) To investigate the role of propagator wakes as zones of pre-existing crustal weakeness; 7) To explore the relationship between local seismicity (both on and off axis) and the physical and chemical changes observed at the borehole sites; 8) To gain knowledge about the full, crustal scale fluid flow at ridge flanks.

Push-Pull Tests: A new Approach to Quantifying In Situ Microbial Activity in the Subseafloor

Mark Nielsen

Major questions about the microorganisms in the ocean crust include: how do they make their living? and, what (if any) role do they play in the biogeochemical fluxes between the earth, oceans and atmosphere? The first step to attack these questions is to understand the metabolic activity of the microbes.

One method that has been proposed to study this problem is called a "Push-Pull Test." Push-Pull tests were developed by civil engineers as a way to quantitatively measure in-situ microbial activity. They were designed to gain a better understanding of microbial activity in bioremediation applications and to aid in the design and evaluation of remediation systems. The tests involve the injection ("push") of a solution with known constituents into an aquifer followed by the extraction ("pull") of the test solution/ground water mixture from the same location. The solution has two main components: a conservative tracer and a substrate designed to contribute to a microbial process in the aquifer, which results in a distinct product. The injection solution has carefully measured concentrations of the tracer and substrate and the extracted fluid is analyzed for the tracer, the substrate and the product(s) of a microbial reaction. As described above, these tests have only been applied in terrestrial settings in bioremediation and site characterization activities. It is our proposal to apply push-pull test methods to the deep hard rock biosphere. Experiments are proposed for several environments including a deep, saline, granitic aquifer in Sweden and basalt formations of the Columbia River Formation and/or Hawaii. Ultimately we propose to conduct a push-pull test on a borehole that is equipped with a CORK and completed in the hard rock environment of the ocean crust (beneath any influence of sediments).

Current planning for the OOI, solication for an operating office, and the planning process for formulating an initial science plan for the program.

John A. Orcutt

The Dynamics of Earth and Ocean Systems (DEOS) program was developed in 1997 to promote long-term observations in the oceans. DEOS, now under the sponsorship of the Consortium for Ocean Research and Education (CORE), supports NSF planning for the Ocean Observations Initiative (OOI) Major Research Equipment and Facilities Construction (MRE-FC) program, advocates the collection of long-term time-series data with the recognition that this is the only viable approach to observe transients and changes and to enhance the signal-to-noise ratio of weak signals. Moored ocean buoys as well as seafloor-cabled systems are technically feasible approaches for making sustained time series observations in the oceans and will be important components of any long-term ocean observing system. DEOS includes measurements over large time and spatial scales including global and coastal observatories and regional networks. The need for real-time delivery of heterogeneous, packetized data, integrated with processing, acquisition, and archiving systems is shared by systems at all scales. Close collaboration with the new Integrated Ocean Drilling Program is essential, especially for the global and regional components of the program. In particular, borehole seismic observatories have several advantages over seismic stations sitting on the seafloor or buried a short distance into the sediments. Monitoring of the hydrology of the continental margins including measurements of permeability, pore fluid pressure, and pore fluid chemistry through time are critical for understanding the role of fluids in the sediments and shallow crust. I shall describe the current planning for the OOI including the solicitation for an operating office and the series of workshops planned for this year and early next year for formulating an initial science plan for the program.

Detecting and Understanding Fluid Pressure Changes of Tectonic Origin in Subsurface Boreholes

Evelyn Roeloffs

Fluid pressure observations in terrestrial boreholes have revealed interesting changes of tectonic origin, among them persistent pressure changes following surprisingly distant earthquakes. In some cases these changes suggest that seismic waves stimulate increased vertical conductance in shallow hydrothermal systems. Temperature observations in seafloor hydrothermal systems have also revealed temperature increases in response to earthquakes. Collecting both temperature and pressure data in a single borehole, ideally in a hydrothermal setting, could constrain possible mechanisms for these changes. Collocated seismometers and strainmeters would also allow measurement of the amplitudes of seismic shaking corresponding to the changes as well as the detection of any permanent deformation. The study of this phenomenon could contribute to a better understanding of earthquake interactions and the dynamic processes maintaining permeability of the crust.

Terrestrial observations in boreholes at Long Valley, California, include fluid pressure, temperature, and strain monitoring, and prototype pressure-temperature instruments capable of operating at temperatures to 150°C, built by Sandia National Laboratories, are under test. Parallel experiments in seafloor environments and intercomparison of data and instrument performance could speed instrument development and scientific progress in a variety of active tectonic settings.

Seafloor Deformation Monitoring with Gravity and Pressure Sensors

Glenn Sasagawa, Mark Zumberge, Scott Nooner

Seafloor geodetic measurements are relatively new, due to problems in applying terrestrial geodetic techniques at sea. Vertical deformation monitoring in particular remains a difficult issue. Gravity and pressure measurements can provide information on seafloor deformation processes.

Gravity measurements are sensitive to vertical displacement (i.e, the free air gradient, -0.308 mGal/m) and mass distribution changes beneath the observation point. Pressure measurements can be inverted for relative vertical displacement. A combination of both measurements can be used to observe and constrain the deformation due to many seafloor features, such as sub-aerial volcanoes and dike structures.

We have developed a deformation monitoring technique using seafloor relative gravimeters and pressure sensors. The instrument package contains three identical Scintrex CG-3M gravimeters housed in pressure cases, along with three identical Paroscientific quartz pressure sensors. Measurements are made on seafloor benchmarks, which provide accurate instrument relocation and a stable observation point. The instrument can be deployed with an ROV or a manned submersible. This system is known as ROVDOG, which stands for Remotely Operated Vehicle deployable Deep Ocean Gravimeter.

ROVDOG has been deployed three times since 1998 in the North Sea, as part of a gas field reservoir monitoring program. In 2002, the system demonstrated a precision of 0.010 mGal in gravity, and 0.75 cm in pressure derived relative depths; the observations took place at a mean depth of 300 m. ROVDOG has also been deployed on the Mid-Atlantic Ridge, at depths over 2000 m.

Global Siting Plan for Borehole Geophysical Observatories in the International Ocean Network

ION Steering Committee[1], R. Stephen (WHOI-U.S.) and J. Orcutt (SIO-U.S.)

[1]A. Schultz, H. Villinger, K. Becker, J. Delaney, , A. Dziewonski, C. Moors, R. Lampitt, J. P. Montagner, B. Romanowicz, K. Suyehiro, P. Tarits

In 1996 the International Ocean Network (ION) committee launched a long-term (decadal) international plan to install long term seafloor geophysical observatories world-wide. A key component of this plan addresses the need to complement the land-based global seismic network with 15-20 seafloor sites, in order to achieve uniform global coverage for the study of deep earth structure and earthquakes. It has now been established that in the oceans, borehole broadband seismometer installations provide significantly better quality data than those on or just below the seafloor. The improved data quality makes possible a range of scientific investigations that otherwise could not go forward. This proposal reviews the progress on existing ODP ION sites and outlines plans for ION related drilling in IODP.

The long-term plan called for three phases: Phase I - Pilot Experiments, Phase II - Prototype Stations, and Phase III - establishment of the global ocean floor observatory network. Phase I is completed, Phase-II is nearing completion, and we are now in a position to start implementing Phase III . These borehole seismic observatories can share where appropriate, power and data acquisition infrastructure and logistical support with other geophysical and oceanographic sensors installed nearby on the seafloor or in the water column. Such facilities will constitute truly multidisciplinary long term observatories in the spirit of ION, as spelled out in its extended 2001 charter. Observatory siting and installation needs to be coordinated with other efforts aiming at developing and deploying such infrastructure (for example the DEOS programs in US and UK, the proposed ARENA program in Japan, and various efforts being planned under EC Framework 6 and its successors).

This proposal focuses on the scientific motivations and siting priorities for drilling seafloor boreholes which will be dedicated to broadband seismic instrumentation. Another type of borehole observatory aims at observing geological processes in situ. While the latter are also part of the general ION goals, they are with some notable exceptions best considered in the framework of focused ODP missions. Sites appropriate from the perspective of global networks typically are chosen far from active geological and geophysical processes, and therefore not optimal for the latter goals. Also, noise considerations make it generally not desirable to combine broadband seismic instrumentation with many other geophysical/geological sensors in the same borehole, although it has been shown that combining broadband sensors with strainmeters and pressure sensors can be done successfully. Where there are opportunities for collocating global network observatories with active process observatories, we have done so.

IODP-OOI sites: towards understanding the geochemistry of the oceans and how the lithosphere thickens with age

John Sclater, Miriam Kastner, Gabi Laske

Among the suite of scientific measurements to be carried out at the combined OOI and IODP sites will be the determination of chemical and fluid flow, down -hole temperature and permeability and the emplacement of a bore hole seismometer. We believe that pre-site surveys involving multichannel seismic, heat flow, seismic refraction surveys and seismic surface wave observations could significantly enhance the scientific value of the actual measurements at the sites. In addition, the combination of the drilling and surveys in carefully selected areas in the deep ocean floor could provide the initial impetus to two other programs to examine the deep ocean crust on a global scale. The first is a program of detailed sites, chosen a few million years apart, to investigate the relation of sediment and crustal physical properties to fluid flow from the ridge crest to 20 million year old crust beneath each major ocean. One of the goals of this program would be determine how much the flow of fluids through sediments on young ocean floor contributes to the overall chemical balance of the oceans. The second is a suite of sites spaced much further apart on older ocean floor to examine the exact nature of the relation between depth, heat flow, lithospheric thickness and crustal age. Understanding these relationships and the ability to subtract the lithospheric seismic signature from global tomographic models is a major objective of the Ocean Mantle Dynamics Project.

Subseaflor biosphere in oceanic crust

Stefan. M. Sievert

A fascinating area receiving increased attention in recent years, is the microbial ecology of sub-seafloor environments. Although the microbial oxidation of geothermally produced hydrogen sulfide, supports dense animal communities surrounding hydrothermal vents, very little is known about the composition and extent of the microbial communities in the interior and subsurface portion of these systems and the global impact of their activities due to its limited accessibility. Up to this point, our knowledge about the biosphere in the oceanic crust is mainly based on indirect evidence and it is only recently that methods were developed to study the microbial communities in this habitat by direct means. Major issues remaining to be resolved are to 1) differentiate between autochthonous and allochthonous microbial populations, and 2) elucidate the activities of the microbes and their interaction with the environment. To address these issues makes it necessary to combine the unique capabilities of IODP to access the ocean crust with establishing observatories at the drilling sites. I would be highly interested in developing an innovative, multidisciplinary research initiative to detect, sample and characterize microbial ecosystems in oceanic crust, something that is already being initiated by scientist here at WHOI. Such an effort will require combining extensive programs of field exploration and experimentation with detailed laboratory work to investigate microbial community composition, processes and the nature of interactions between microbes and minerals. Equipping the advanced CORK system with in situ experiments offers unprecedented opportunities to access the sub-seafloor biosphere and to monitor microbial communities and their activities over time.

An OOI/IODP Case Study: Borehole Observatories in Deep Riser and Riserless Holes on IODP

R. A. Stephen

I. Introduction

There are many scientific problems and technological capabilities that have been discussed for borehole observatories. To consider all of them in a single discussion can be very confusing and it is often convenient to focus on particular case studies which involve only a subset of the overall parameter space. Once a particular package of scientific justification and technical methodology has been established, other science and technology can be addressed in a complementary fashion. In this spirit the main focus of this discussion will be on borehole seismic observatories for subduction zone (plate boundary) drilling.

Borehole geophysics will play an important role in the subduction zone drilling on IODP. Experience on the previous drilling programs has indicated that there are three basic styles of borehole geophysical measurements: 1) conventional well logging, 2) two-ship borehole experiments (such as offset VSP's that require the drill ship to be on site) and 3) long-term borehole experiments (CORK's, strain installations, ION broadband seismometers, etc). All three categories apply to both riser and non-riser holes. In addition to enabling new styles of borehole geophysical studies, observatory infrastructure can facilitate and expand the utility of some conventional borehole measurements that are usually made from the drill ship. Most of what follows is based on Vertical Seismic Experiments (VSP's) but other measurements have similar issues.

II. Scientific Justification for Borehole Seismology in Subduction Zone Drilling

Validating Surface Seismic - Scales of Observation

Few question the wisdom of drilling a borehole to provide "ground-truth" to the analysis and geological interpretation of seismic and other data acquired at the surface. Of course this is one of the primary motivations behind past, present and future ocean drilling programs. Because of the large differences in the scales of observation, however, the section intersected by the well (with observations from cores at horizontal scales less than 6cm and observations from well logs at horizontal scales less than a few meters) often does not correlate well with the seismic section (with horizontal scales of 100's of meters or more). For this reason, regardless of the geological scientific justification for drilling there is ample geophysical scientific justification for VSP's.

Validating Surface Seismic - Interference and Multi-path Effects

There have been many examples of the importance of normal incidence and offset VSP's on the DSDP and ODP programs including the origin of mid-sediment reflectors (from interference effects in thin layers), the nature of Layer 2/Layer 3 boundary in oceanic crust, and the investigations of gas hydrate deposits. In these cases and others it has been very useful to acquire VSP's using sources with similar bandwidth to the seismic sources in order to resolve the interference and multi-path effects that often affect the character of reflections on seismic record sections. The thorough ground-truth that boreholes and VSP's provides often demonstrates the importance of sophisticated seismic techniques such as true amplitude processing, amplitude versus offset (AVO) analysis, 3-D seismic, three-component seismics (with polarization analysis to study the effects of anisotropy) and pre-stack migration. Normal incidence VSP's provide a direct analog to the "normal incidence reflection profile" which is a common step in the multi-channel data analysis process. Offset and walkaway VSP's are often just as important as normal incidence VSP's in validating surface seismic Because of shear waves (which are not usually excited at normal incidence but are frequently observed on offset profiles), other amplitude versus offset effects, and anisotropy.

Extrapolating the Geological Structure Away from the Well

Knowing how the seismic wave field correlates with the geological structure at the borehole gives more credibility to interpretations of the seismic data in the same region but away from the borehole. On NantroSeize for example, significant lateral heterogeneity exists along the decollement reflection (as indicated by "bright spots") but it would be prohibitively expensive to directly sample each category of reflection along the decollement either along or across strike. There is no alternative but to use seismic record sections to interpret the subduction zone region, so we should understand the evolution of the seismic wavefield at the few borehole locations that we can afford. Results from detailed studies at the borehole can then be extrapolated throughout the region.

Monitoring Time-Dependent Effects

The notion of "time lapse" seismology goes back at least 20 years when Aki proposed the method for analysis of hydrofracturing in petroleum and geothermal wells. The character of the seismic reflections in subduction zones can vary with time for at least three reasons: 1) when the state of stress on a horizon of interest varies with time a) as a result of an earthquake on the fault (over seconds), b) as a result of an earthquake in the region which changes the regional stress pattern (Coulomb stresses, over days, months and years), or c) as a result of slow deformation (over tens of years); 2) when the drilling process itself changes the in situ pressure conditions on the fault by relieving whatever pressure anomaly may have originally existed (over hours to years); and 3) when the seismic acquisition system changes. Reasons 1) and 2) have significant geological consequences and will affect the application of seismic methods to understanding subduction zone processes. Reason 3) is a common phenomenon. It is often very challenging to get similar seismic profiles from two different but similar surveys at the same place. There are a lot of reasons for this, including changes in small scale lateral heterogeneity and changes in frequency and wavenumber content of the observed field, but it is good practice in time lapse surveys to change as few aspects of the acquisition system as possible.

III. Some Typical and Proposed Borehole Seismic Experiments

1) Conventional Well-Logging and Normal Incidence VSP's

It is unclear at the moment how conventional well logging will be run on the IODP platforms. Well logging is very important because the core recovery, particularly in hard formations is incomplete. Also cores are frequently disturbed and logging provides measurements of conditions in situ. Clearly "routine" logging needs to be carried out at various stages of the drilling process. For example, some measurements need to be made in the open hole before casing is installed. Since well logging is not strictly an "observatory" technology we will not address it further, although it qualifies as an important "survey technique" as background information for successful observatory installations.

Since our best images of the interior of the earth are based on seismic methods, one important goal of many deep boreholes is to provide ground truth and to calibrate seismic record sections. Borehole seismology is one of the few tools we have to link the borehole scale (defined by cores and well logging) to the regional scale (defined by multi-channel and refraction seismics). Also given the significant lateral heterogeneity observed along strike in all subduction zone environments, extrapolating the borehole results along the subduction zone will require a thorough knowledge of how the reflected seismic wave field is created and how it relates to the borehoe observations. Normal incidence VSP's have proved very useful in the past in correlating core and well log observations with regional multi-channel and single-channel seismic records. Although normal incidence VSP's are a "conventional logging service" run during and shortly after drilling, they can also be carried out in an observatory setting where a permanent array of VLF (1-100Hz) sensors are permanently installed in the well or adjacent to the casing. In this mode, normal incidence VSP's can also be used to study time dependent effects such as changing in situ pressure conditions before and after drilling or the changing stress regime after a major earthquake.

2) Two-ship Experiments and Offset VSP's

Offset VSP's are another style of borehole seismic experiment that have proved useful in the past particularly to define shear wave velocity structure (since shear waves are not usually generated at normal incidence). A second ship to fire seismic sources out to ranges of 30km or more is used in addition to the drill ship which records the borehole seismic data. Offset VSP's have been used in gas hydrate and crustal and upper mantle anisotropy studies. Since the borehole equipment is very similar to the VSP tools used in conventional logging (usually a three component seismometer instead of a single vertical component seismometer), it is often convenient, but not always necessary, to run the offset VSP's while the drill ship is on site. A permanent borehole array installed as a component of a borehole observatory would facilitate repeat offset VSP's. The borehole seismic data would be acquired by the observatory infrastructure, and only a shooting ship would be needed.

3) Time-lapse VSP's

Time lapse VSP's require dense strings (typical sensor separation of 10m or less) of VLF sensors. These can be particularly valuable in subduction zone settings since as the state of stress and fluids along faults changes so will the character of the seismic reflections. Since these reflections are often the consequence of complicated interference and multi-path effects VSP data is often useful in understanding what changes in in situ properties are causing changes in the seismic data. Also since VSP data provides the link from borehole to MCS scale, it is an important tool in extrapolating the results from the borehole throughout the region. If a dense string is permanently deployed in a borehole, it can easily be used for offset as well as normal incidence VSP's.

4) Long-term Borehole Experiments and "Spin-off"Projects

There is ample geophysical scientific justification and an excellent historical track record both in the petroleum industry and in deep sea drilling for the above VSP projects. Any drilling program to seismic targets in subduction zones should include normal incidence VSP's, offset and/or walkaway VSP's and time-lapse VSP's. However when we start to consider the necessary infrastructure for time-lapse VSP in particular there are other spin-off scientific projects that could be carried out. The infrastructure for long-term borehole seismology is similar to that for CORK's and strain meters which are discussed elsewhere in this report. Additional long-term borehole seismic experiments also fall into a number of categories:

a) Monitoring and locating micro-earthquakes

For time-lapse VSP discussed above, it would be best if we had a permanent array of closely spaced VLF (about 5-100Hz), three-component sensors either in the well or in the adjacent casing. Once the array is in place why only use it periodically for VSP's? It would make sense to record the data continuously to detect micro-earthquake events. The vertical array would help to improve the locations of events already being observed by land surface and seafloor seismometers, but also being closer to the fault and potentially in a lower noise environment, the vertical array may detect smaller events than the other systems. Passive micro-earthquake monitoring would be a natural extension of the VSP infrastructure. (A permanent array just for seismic monitoring would not need the same sensor spacing as a permanent array for VSP's. Some modeling would be required but perhaps only a sensor every 500m's for monitoring versus a sensor every 5-10m's for VSP.)

b) Cross-well tomography

Also with a permanent VSP array in place, there is the potential to carry out cross-well seismic tomography if a second hole is drilled near-by. In a tomography experiment seismic "volume" anomalies are detected using transmitted paths. Sharp discontinuities which are necessary to generate reflections from "surfaces", for multichannel surface seismic surveys for example, are not required for tomography. Although it is unlikely that a hole would be drilled just for cross-well tomography, it is possible that closely spaced holes may be drilled for other cross-well experiments (water sampling, permeability, etc) or for sampling different sections along a fault (bright versus dull spots for example).

Dense strings (as for time-lapse VSP's) of VLF sensors provide the data necessary for cross-well tomography. To work properly the wells must be drilled deeper than the horizons of interest and they need to be drilled close together (separations comparable to depths) to get adequate ray coverage. Too often wells stop at the horizon of interest and cross-well tomography becomes difficult to implement.

c) Broadband Seismometer Installations (ION)

Broadband seismometers (typically 0.001-10Hz) in boreholes on the ocean floor have been proposed by ION to extend the global seismic coverage to the ocean basins. These installations are usually justified on the basis of global studies (for whole earth tomography, for example), but they can also be used in regional studies to improve earthquake locations and source mechanisms in critical areas such as offshore Japan or California. It would make sense for any seismic monitoring effort in a subduction zone to include a strong motion and broadband seismometer. These sensors would provide direct measurements in the near-field of any earthquake activity along the fault being drilled. Being in a borehole they also would have a better ambient noise environment and would have improved coupling for observing local, regional and teleseismic events.

IV. Technical Challenge: Tubing-with-Casing Technology

Obviously the projects outlined above (and others) need to be justified in terms of the scientific payoff and costs. In the planning process, however, important constraints can be placed by the available technology.

To date on DSDP and ODP there has been one conduit down the center of the well. If sensors are cemented in the bottom of the well then it is not available for other experiments or future drilling. "Tubing-with-casing" technology provides an opportunity to have multiple conduits down the well. It involves placing hollow tubing either outside of a casing string or between casing strings. The tubing is often cemented in place along with the casing. Some tubes can be used for permanent sensors which are cemented in place, other tubes can remain open for repeated lowerings of a variety of sensor strings, and the hole can stay open for deeper drilling.

If IODP develops a "tubing-with-casing" technology, in both riser and riserless drilling, it will have significant consequences for the efficacy of long-term geophysical measurements. Long-term experiments can be planned and carried out essentially independently of the drilling process. New tools that we have not even thought about now can be deployed as the technology of borehole instrumentation develops (particularly with respect to temperature and nanotechnology).

"Tubing-with-casing" technology is extremely important for long-term borehole experiments in subduction zones, but it is a technology that can be exploited on any IODP holes with multiple casing strings. It is used in the petroleum industry to permit instrumenting of boreholes for reservoir monitoring projects and perhaps we can take advantage of their experience.

Since the potential availability of tubing-with-casing places important constraints on the types of borehole geophysical observatories that can be proposed for subduction zone and other plate boundary projects, a workshop should be held to familiarize the IODP drilling and scientific communities (riser and riserless) with the pros and cons of this technology. Speakers should be invited to address the issues of installing tubing in deep boreholes (perhaps with multiple laterals), of placing sensors in tubing (what types of sensors are commonly used, what are the important issues), and of related technologies (for example, combining borehole arrays with seafloor arrays for reservoir monitoring and other time lapse projects).

Ocean crustal drilling at the Hawaii-2 observatory

R.A. Stephen, J. Kasahara, G.D. Acton ODP Leg 200 Scientific Party

The primary goal of Ocean Drilling Project Leg 200 was to drill a suitable hole for a borehole seismometer at the long-term Hawaii-2 Observatory (H2O) site (see below). This was accomplished in Hole 1224D, where we installed a reentry cone and cemented casing 30 m into basaltic basement 1.48 km northeast of the H2O junction box. Above basement there was 28 m of soft, red clay. The cased basement interval, in which a borehole seismometer will be installed in 2004, consisted of massive basalt flows that had been cemented by calcite. This should provide good coupling for the seismometer to true earth motion. We also drilled a second single-bit hole, which was cored and logged, within 20 m of the first to a depth of 145 m into basement. The second hole was left with a free-fall funnel so that it also could be reentered using the wireline reentry technology to carry out other borehole experiments at the site. A suite of shipboard physical, well log, chemical and microbiological analyses that can be used to characterize the crust surrounding the observatory, was also carried out.

The successful cultivation of oxidizing bacteria and the microscopic indication of further microbial structures within a cavity of basaltic rock confirm the presence and even activity of microbial life not only in deep marine sediments, but also in the Paleogene oceanic crust from the North Pacific. We tested a deep 3.5-kHz source that could be deployed on the VIT frame to inspect the shallow structure of the seafloor at a higher spatial resolution than conventional echo sounding. Measurements of ship noise during the drilling operations were also acquired on the shallow buried seismometer at the Hawaii-2 Observatory. The Hawaii-2 submarine cable system is a retired AT&T telephone cable system between San Luis Obispo, California, and Makaha, on Oahu, Hawaii. The cable system was originally laid in 1964. In 1998 investigators from Incorporated Research Institutions for Seismology (IRIS), the University of Hawaii and Woods Hole Oceanographic Institution installed a long-term seafloor observatory about halfway along the cable (~140°W, 28°N). The junction box has eight underwater make-break connections. About 500 W of power is available from the junction box, and there is ample capacity for two-way, real-time communications with seafloor instruments. Data channels from the seafloor can be monitored continuously via the Oahu end of the cable to any lab in the world.

A borehole, seafloor and water column observatory for establishing relationships resulting from tectonic and oceanographic forcing on fluid flux, gas hydrate, and biological processes in an accretionary complex

Anne Trehu and Marta Torres

Recent studies have revealed links between tectonic and hydrothermal activity in the ridge environment. We believe that tectonic forcing also plays a significant role in fluid flow in accretionary complexes; however, these inter-relationships have not been as well documented in these settings because of the absence of long-term measurements on the seafloor and in the subsurface. This feedback between oceanographic and tectonic forcing is likely to be even more complex in gas hydrate bearing margins, where multiple forcing factors with various time scales act simultaneously resulting in complicated behavior that required long time series to unravel. For example, a seismic event may induce new fluid path formation, the enhanced fluid flow may trigger diagenetic reactions and gas hydrate formation, which in turn will constrict and eventually block these paths. Understanding these links is important for our understanding the factors that control the size and location of earthquakes, the role of gas hydrates in slope stability and the global carbon cycle as well as other issues of scientific and societal importance. An observatory to understand these processes must include a variety of different sensors deployed both within a borehole and on the seafloor.

Borehole seismometers, strain meters, flow meters, temperature and pressure sensors, and chemical samplers are needed in one or more vertical arrays. The number and location of boreholes and the depths at which instruments should be placed in each borehole should be decided based on comprehensive 3D seismic, geophysical imaging and prior deep sea drilling observations. Targets include sampling below, at, and above the BSR, as well as monitoring potential pathways of fluid flow. The borehole experiments should be complemented by arrays of instruments on the seafloor to record long and short period seafloor deformation; fluctuations on temperature and heat flow; water, gas and chemical fluxes in and out of the seafloor; and the biological response to the chemical perturbations of the system. Both borehole and seafloor observatories should include mechanisms for interactive experiments, such as pumping, tracers and biological incubations. Additional instruments in arrays within the water column above borehole sites should include geochemical samplers and sensors as well as acoustic and optical sources and receivers for active imaging and quantification of material fluxes in bubble plumes and suspended particles.

Borehole Observatories in Shallow Reference Sites, Nankai Seismogenic Zone Experiment

Michael Underwood and Juichiro Ashi

We have submitted a revised proposal to iSAS to drill three shallow reference sites during Phase 1 of the Nankai Seismogenic Zone Experiment. Two sites are located seaward of the trench; one is above a subducting basement high, the other above a basement plain. The primary goal here is to show how inputs to the subduction zone (i.e., lithostratigraphy, sediment composition, physical hydrogeology, geotechnical properties, fluids) change in response to variations in basement topography. The third site is located at the toe of the accretionary prism. The goals there are to pinpoint the stratigraphic position of the frontal decollement, document the effects of structural partitioning across the decollement, and characterize early-phase deformation fabrics within and adjacent to the plate boundary fault. Detailed plans for borehole observatories are not included in the existing proposal because site-survey data (especially high-resolution heat flow) are not extensive enough to permit thoughtful design of experiments or to pick optimal locations for testing specific hypotheses. The NanTroSEIZE community, however, intends to augment Phase 1 coring and downhole measurements with an array of observatories that would monitor physical hydrogeology and fluid temperature, sample fluids in situ (including igneous basement), and permit seismology and/or geodetic experiments.

Lessons learned from monitoring the chemical composition of borehole fluids

C. G. Wheat, H. Jannasach, and M. Kastner

OsmoSamplers recovered from ODP Sites 1024 and 1027 provide insights into the rate at which deep-sea boreholes recover after drilling. In contrast to thermal and pressure data, chemical data illustrate that recovery can take years. One borehole recovered in 820 days whereas the other has yet to recover and would likely require a total of 9 years to recover. Surprisingly there appears to be little contamination considering the expansive surface area of steel casing. In contrast, the chemical compositions of formation fluids that vent from two boreholes on the eastern flank of the Juan de Fuca Ridge have experienced some contamination during ascent, thus altering trace element concentrations. Both experiment would have greatly benefited the use a packer below the casing, thus removing contact with sediment and steel casing. This packer could include a tube that would connect the open borehole below the packer with a manifold at the seafloor, thus avoiding contact with grease-covered steel casing yet providing a pristine fluid for in situ experiments at the seafloor. Such a new CORK design would allow boreholes to recover faster (on the order of weeks to months). A faster response is desired when conducting experiments such as controlled tracer injections to test hydrologic properties. One could also experiment with the subsurface biosphere, by injecting nutrients and measuring responses. Similarly, one could study crustal alteration processes in a natural setting. Ideally, there would be a series of boreholes that represent a range in formation fluid compositions and temperatures.

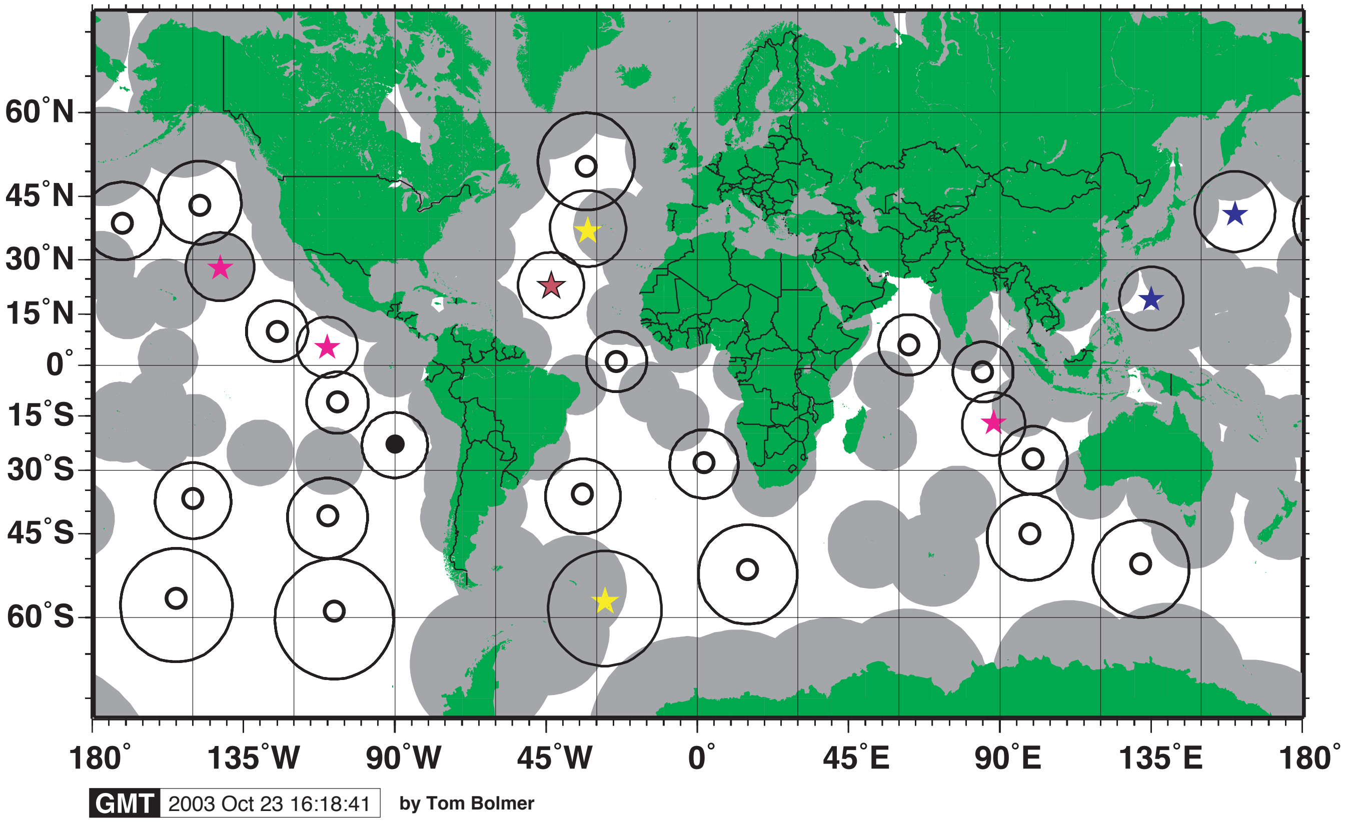

Figure IV-1. Summary of the role of ocean borehole sites in global seismic coverage. Grey shaded regions indicate surface coverage out to 1000 km from continent and island stations (distorted in the projection). White spaces are gaps in land-based coverage. Existing and proposed ocean stations are indicated by symbols surrounded by black circles (at approximately 1000 km radius). Symbols show different levels of progress at the ocean sites: red star - MAR test site (OSNPE and Japan Sea test sites not shown); blue stars - presently operating borehole observatories (Japan Trench regional sites not shown); maroon stars - sites drilled but not yet instrumented; solid black circle - proposed ION phase 2 site, not yet drilled; small open circles – ION phase 3 sites; yellow stars - phase 3 B-DEOS global sites (Reykjanes Ridge and Drake Passage B-DEOS regional sites are not shown). Figure modified from Stephen et al, (2003).

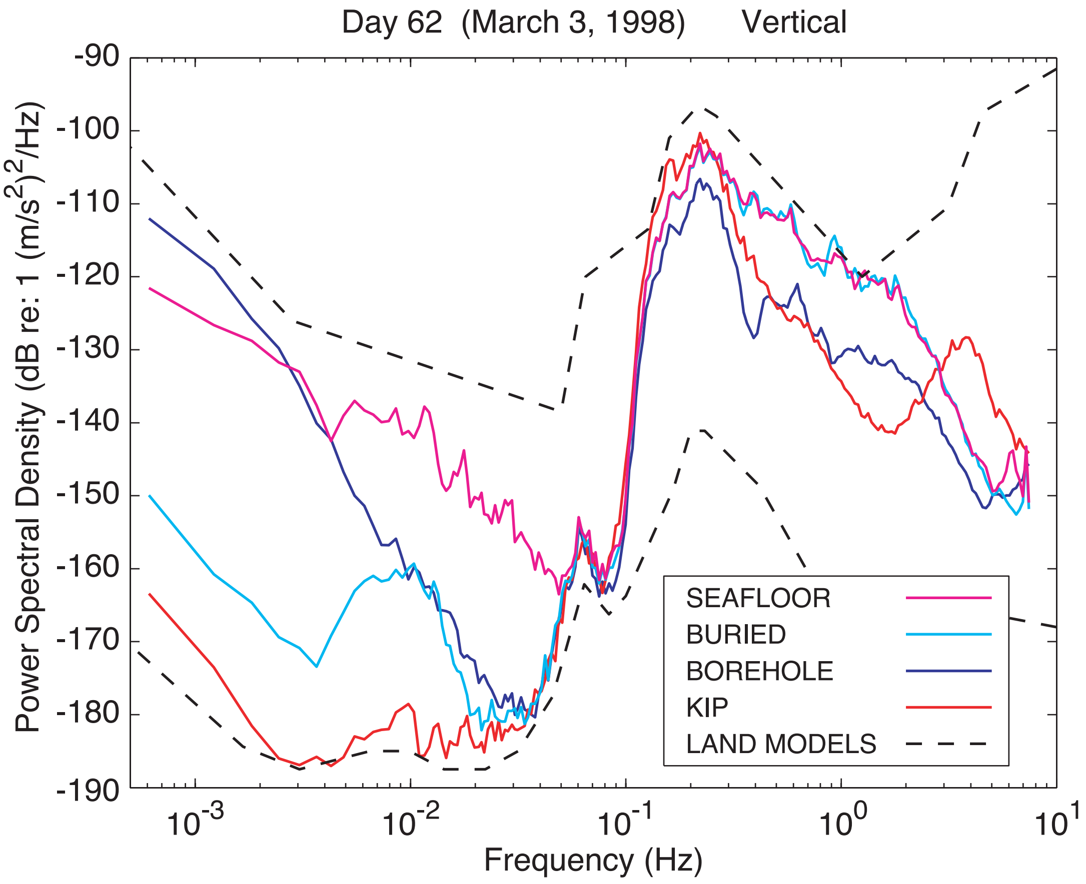

Figure IV-2. Comparison of seismic spectra recorded in several settings, including seafloor boreholes, seafloor, buried (near seafloor), and land stations. Three broadband seismometer configurations on the OSNPE (seafloor, buried and borehole), are compared to the Kipapa GSN station on Oahu, and high- and low-noise USGS spectral models based on land observations.

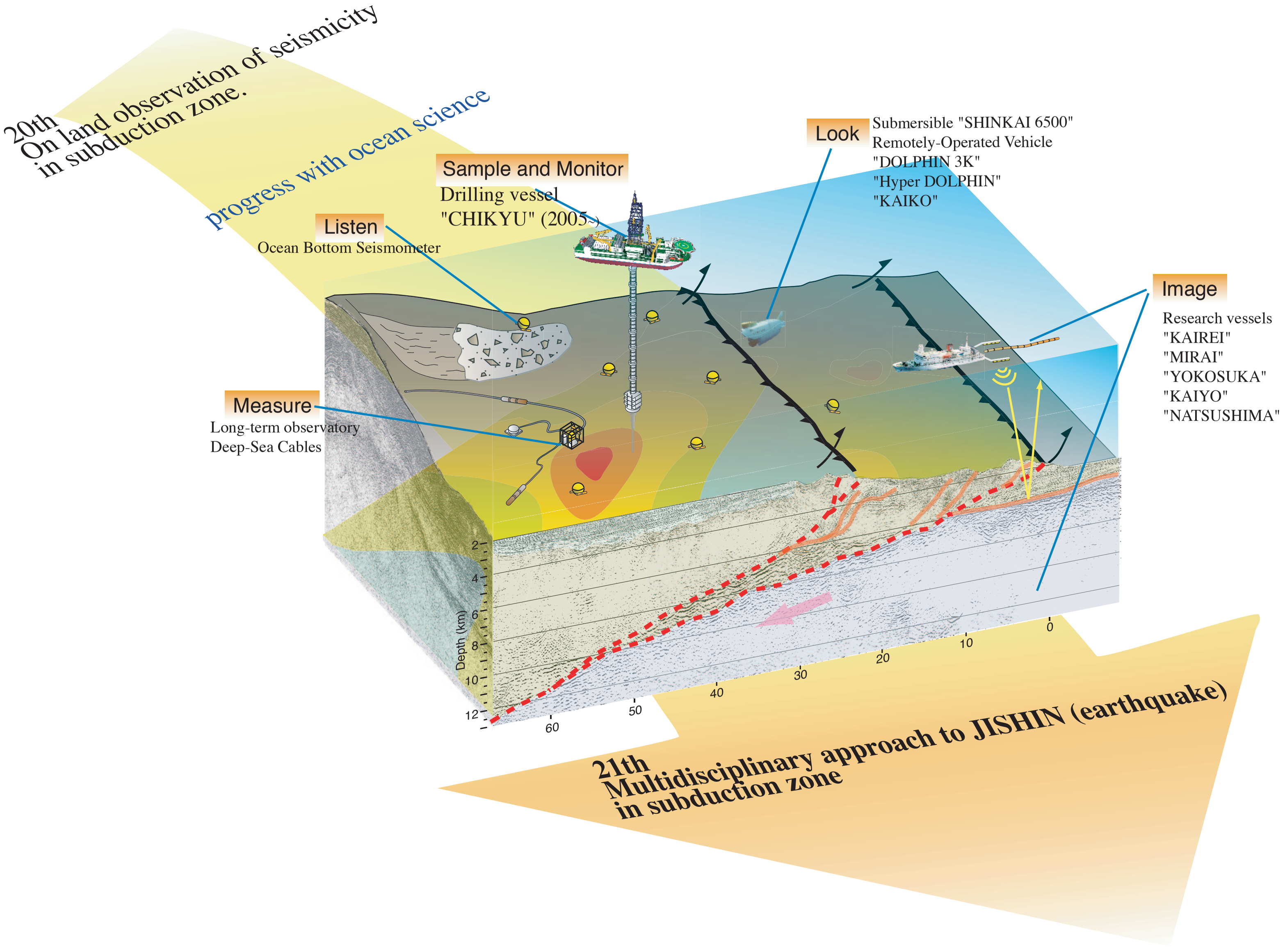

Figure IV-3. Schematic cartoon showing elements of an integrated observatory for subduction zone earthquakes. Elements of the observatory include: (1) instruments in an array of boreholes monitoring strain, pore fluid pressure, temperature, and sampling continuously for fluids; (2) seafloor instruments monitoring displacement (geodesy), OBS's, fluid flux, and fluid chemistry; (3) repeated surveys for seafloor visual, E-M, sidescan, and heat flow in response to earthquakes; (4) instruments and repeated surveys in the water column to monitor potential plumes of fluid expelled and their relationship to seismic events. The borehole observatory array would include paired sites for cross-hole experiments, characterization of volumetric properties.

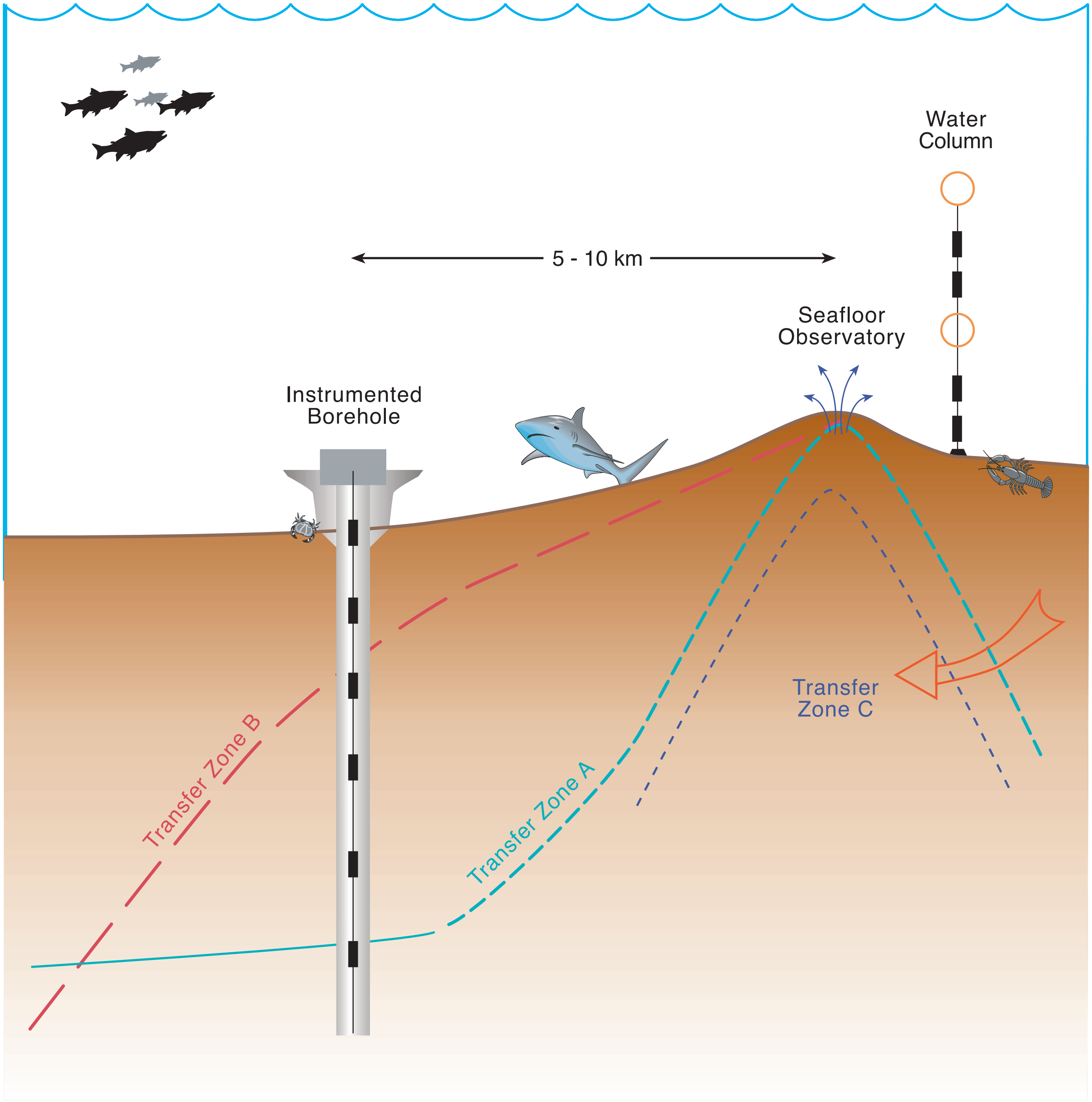

Figure IV-4. Schematic representation of a coupled "bottom-to-top" observatory designed for quantifying fluid fluxes and geochemical processes in the seafloor, based on the concept of a "transfer zone." The general system involves a deep hydrologic reservoir by instrumented borehole; a transfer zone and seafloor manifestations. In this cartoon the reservoir represents igneous crust beneath the sediments at ridge flank, but the site could just as easily be within and accretionary complex beneath a BSR. The transfer zone in ridge flanks is represented by hydrated sediments and crustal outcrops (transfer zone A). In gas hydrate provinces, hydrocarbons migrate through structurally or lithostratigraphically controlled horisons (transfer zone B). At the ridge axis, fluid flow is generally focused within and near the neovolcanic area (transfer zone C). Seafloor observatories at sites of fluid venting include axial vents, off-axis springs, and cold seeps. The water column serves as an integrated recorder of seep and vent activity.

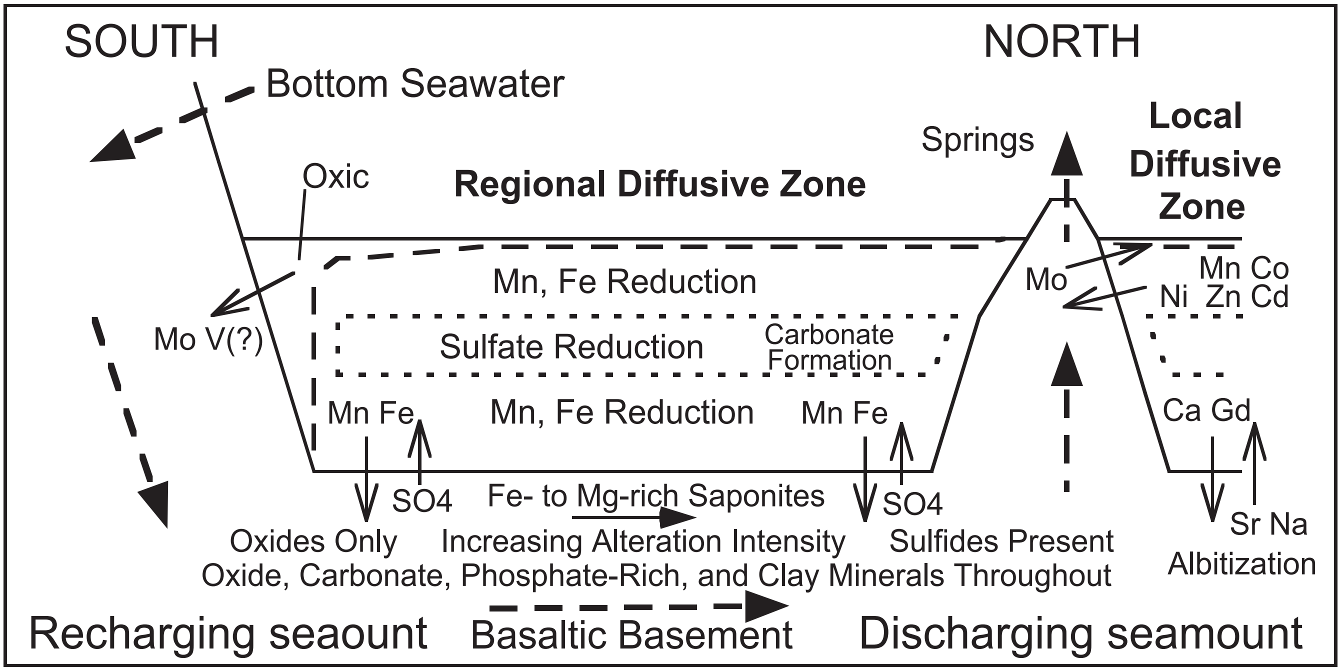

Figure IV-5. Conceptual diagram of seawater flow and reaction within the crust on the flank of a mid-ocean ridge. Bottom seawater enters basement where basaltic outcrop is exposed and flows laterally through basement before venting at another basaltic outcrop. Along this flow path seawater warms and becomes increasingly altered. Alteration occurs via reactions within basaltic basement and as a result of diffusive fluxes between the overlying sediment pore fluids, which have been altered by diagenesis. This particular diagram represents the expected path of flow through the crust and reactions within the crust on the eastern flank of the Juan de Fuca Ridge. In this case, seawater enters basement at Grizzly Bare Outcrop and flows to the northeast where it warms from about 2 °C to 63 °C before it vents at Baby and Mama Bare Outcrops (dashed arrows) [Fisher et al., 2003; Wheat et al., 2000; Wheat and Mottl, 2000; Wheat et al., 2002]. The combination of reaction within the crust and diffusive exchange with sediment pore waters produces a highly altered formation fluid. Borehole observatories could be used to examine the rates and impacts of these kinds of processes.

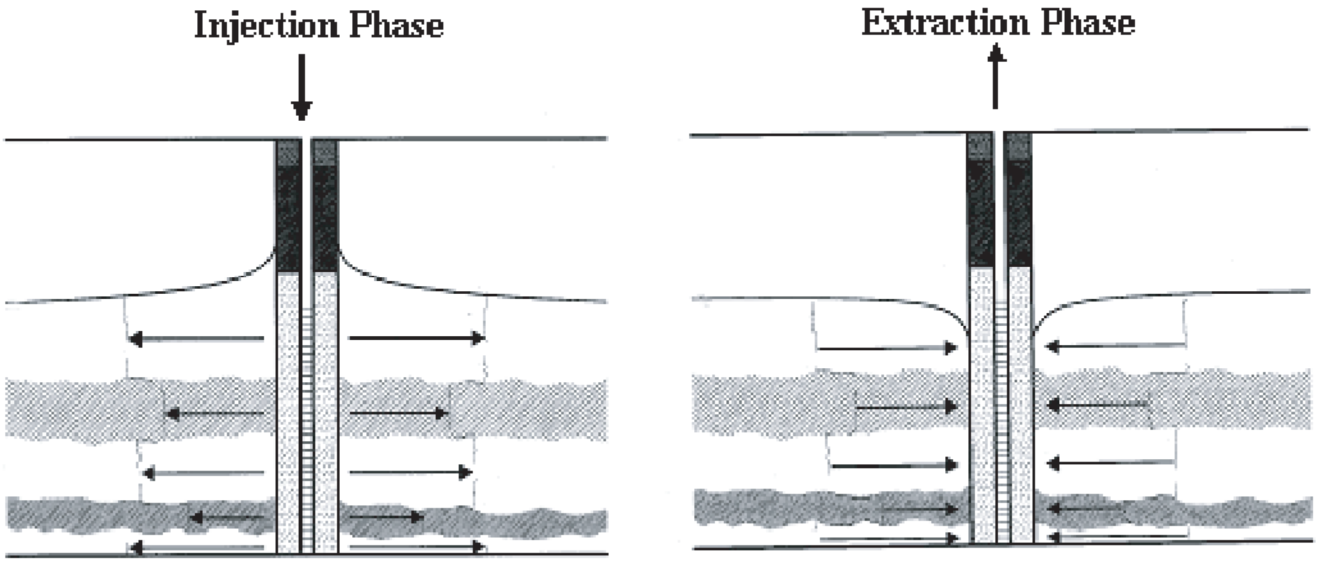

Figure IV-6. Schematic drawing of push-pull test concept. Solution with conservative and reactive components is injected into the subseafloor and later extracted from the same location. Changes in concentration of reactive components allow the determination of in situ microbial reaction rates.