A New Vision for Scientific Ocean Drilling

A REPORT FROM COMPOST-II: THE U.S. COMMITTEE FOR POST-2003 SCIENTIFIC OCEAN DRILLING

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EXECUTIVE SUMMARY

PREFACE

The natural rhythms of Earth's climate, plate motions, and volcanism vary on a variety of time-scales; understanding the reasons for such changes poses an urgent challenge. Ocean drilling, used to confirm the theory of plate tectonics and to document changes in ocean circulation and climate, is now also needed as part of a larger global strategy to solve pressing problems facing humankind.

The Deep Sea Drilling Project (DSDP), the International Phase of Ocean Drilling (IPOD), and the Ocean Drilling Program (ODP) together span more than a quarter century of scientific achievements that are impressive by any standard. Through scientific ocean drilling, paleoceanographers have begun to document changes in the ocean's carbon budget, oscillations in rates of formation, depth of penetration, and chemistry of deep water masses, and abrupt shifts in climate response to orbital forcing. ODP has drilled into active hydrothermal systems in the oceanic crust, where volcanic- and sediment-hosted sulfide mineral deposits are forming, to provide insight into the development of these deposits which may aid in land-based mineral exploration efforts. In subduction zones, drilling scientists are using innovative techniques to understand processes of rock deformation and the role of fluids in faulting and seismicity. Most recently, ODP has uncovered spectacular evidence of the cataclysmic meteorite impact that may have led to the demise of the dinosaurs at the end of the Cretaceous.

Yet, unraveling phenomena such as long-term ocean and climate change and the nature of the deep oceanic lithosphere (which comprises more than half of Earth's surface) will require a global observational framework and new technological developments. We must take a more expansive, ambitious approach to ocean drilling for study of many of the active geologic processes, like earthquakes, volcanic eruptions, and sea-level changes that will help to shape the future of humankind on Earth.

RECOMMENDATIONS

The scientific objectives envisioned by the U.S. community for the 21st century, as outlined in the 1993 National Research Council (NRC) report entitled "Solid-Earth Sciences and Society," the 1996 ODP Long Range Plan (LRP), and other recent scientific planning documents (many of which are summarized in this report), can only be addressed through an integrated approach, of which a drilling program is a critical component. Accordingly:

1) COMPOST-II, acting on behalf of the U.S. community, affirms its commitment to a new international scientific ocean drilling program post-2003 to solve outstanding scientific problems of a global nature.

2) COMPOST-II thinks that scientific ocean drilling in the 21st century must be defined more broadly, to include predrilling site assessment, drilling and sampling, and post-drilling observations and experiments. Scientific ocean drilling represents a cascade

of diverse activities and investments, from the formulation of scientific hypotheses to post-drilling analysis, integration and publication. If the U.S. community is to participate fully in an enhanced scientific ocean drilling program, we must expand and integrate:

- site-appropriate predrilling characterization (e.g., high-quality 2-D and 3-D geophysics, piston coring, multibeam bathymetry and side-scan sonar, submersible/ROV characterization of the seafloor, etc.);
- post-drilling utilization of boreholes for observation, monitoring, and testing of active processes and studies of whole-Earth structure; and
- post-drilling support of scientific experiments and personnel, which results in data synthesis and formulation of new hypotheses.

3) COMPOST-II endorses the LRP multi-platform approach to the accomplishment of U.S. scientific objectives. This will require a capability to drill and sample in water depths from the beach to the abyss, including:
   - complete recovery of continuous, undisturbed, high-sedimentation-rate sections across a diverse suite of geologic environments and ages;
   - improved recovery and penetration of difficult-to-sample lithologies (e.g., young, fractured basalts) and geologic environments (e.g., overpressured sections); and
   - new capability to reach subseafloor depths in excess of 2 km.

4) COMPOST-II recognizes that the U.S. community remains committed to investigator-driven science. While 21st century scientific ocean drilling will often be allied with major geoscience initiatives, JOIDES or its succeeding advisory structure must be responsive to new ideas from individuals as well as from these collective efforts.

5) COMPOST-II supports education and outreach programs that aim to advance the understanding of earth processes through drilling-related efforts for K-12, undergraduate and graduate learning programs. Specific efforts include:
   - CD-ROM and web-based learning exercises;
   - distinguished lecturer series, with integrated earth-studies opportunities seminars; and
   - private, public, and industry-sponsored fellowships to advance exceptional masters and doctoral candidates.

6) COMPOST-II encourages development of active partnerships with diverse sectors of the U.S. business community (e.g., petroleum, computing, communications), which will focus on direct participation in scientific ocean drilling:
   - as proponents of drilling proposals;
   - through industry funding of drilling- and science-related activities;
   - by means of data exchange for site augmentation, drillsite design, etc.; and
   - through cooperative development and testing of new technologies.

Compost-II Report

Background

COMPOST-II was established at the behest of the U.S. Scientific Advisory Committee (USSAC). USSAC's charge to the committee, as relayed from the Ocean Sciences Division of the National Science Foundation (NSF), was as follows.

To assess the type and level of U.S. interest in scientific ocean drilling beyond 2003:

- what research objectives does the scientific ocean drilling community wish to pursue?
- what facilities and funds will be required to achieve those objectives?

COMPOST-II is the successor to COMPOST-I, a 1993 committee which considered a similar charge from JOI for the post-1998 period, now known as Phase III, of the Ocean Drilling Program (ODP). Members of COMPOST-II were chosen carefully to represent as impartially as possible the U.S. earth sciences community as a whole.

COMPOST-II met at RSMAS, University of Miami, on February 16-17, 1997; this report is the result of that meeting, and of a review of the draft report by USSAC at The Woodlands, Texas, on March 6-7, 1997.

Rationale

A comprehensive 1993 National Research Council (NRC) report, entitled "Solid-Earth Sciences and Society," has outlined priority scientific research objectives in ocean research as embraced by a large community of U.S. earth scientists (22 panels), most of whom have not been associated with ODP or its predecessors. There is remarkable consonance between the scientific priorities outlined in the so-called "Wyllie Report" and those espoused in the 1996 ODP Long Range Plan (LRP), only partly because that report also draws on recommendations from other "initiatives," including the 1990 ODP LRP. The overall goal of the NRC Report is to promote research that will result in a better understanding of the behavior of the Earth system, past, present and future, particularly by studying processes and linkages among components of the system. The stated main objectives of the research priorities are to assure sustained supplies of natural resources, mitigate geologic hazards, and allow humankind to adjust to or mitigate the effects of global change. General research areas paraphrased from the NRC document are: 1) global paleoenvironments and biologic evolution; 2) global geochemical and biogeochemical cycles; 3) fluids in and on the Earth; 4) dynamics of oceanic and continental crust; and 5) dynamics of the core and mantle.

Out of eight "top priority" research themes in the "Wyllie Report," six are directly relevant to ocean drilling science objectives. These objectives, and their associated "high priority" themes, are to:

1) coordinate efforts to understand the last 2.5 million years of environmental and biological change, characterization of the last 150 m.y., and exploration of the record prior to 150 m.y. ago;
2) establish how geochemical cycles worked in the past, construct biogeochemical cycle models, and assess their operation at present;
3) investigate the 3-D distribution of fluid pressure and composition in the crust, as well as model fluid flow in sedimentary basins and assess the influences of microbial processes;
4) intensify efforts to understand crustal deformation and increase comprehension of crustal evolution and

landform response to tectonic (and climate) events;
5) mount an integrated attack to understand mantle convection, the origin and variation of the magnetic field, and the nature of the core/mantle boundary; and, finally,
6) define and characterize regions of seismic, landslide and volcanic hazard.

Scientific ocean drilling is suggested as one of many tools that can be used to solve these problems; ODP is suggested as a relevant international program for most of these objectives.

In October 1993, COMPOST-I examined the major scienctific objectives formulated by the U.S. marine earth sciences community, in light of facilities and technology then available or envisioned. COMPOST-I specifically formulated a set of recommendations regarding the role of U.S. science in ODP. All of these recommendations continue to have merit; some have been considered and incorporated into ODP. Others have yet to be implemented. First and foremost (see Recommendations on the following page), COMPOST-II reaffirms that "a scientific ocean drilling program" will continue to be an essential component of U.S. earth sciences research beyond 2003. COMPOST-II also reemphasizes that such drilling-related research should remain global and international; these characteristics are among those that have kept scientific ocean drilling in the forefront of ocean sciences research over the last several decades.

However, COMPOST-II recognizes that post-2003, scientific ocean drilling must become more broadly defined than it has been in the past, or is at present. U.S. science proposed for the drilling program (see supporting statements below) demands such a redefinition, because global ocean sciences research is evolving towards a complex experimental approach in which drilling is but one tool among many. In the context of the multi-platform complexity envisioned in the new ODP LRP, a "scientific ocean drilling program" for the 21st century must take into account *all* phases of the drilling process, of which actual drilling and complete sampling of a global array of holes is but a part. Such a program consists of several critical and interrelated phases:

- **Predrilling site characterization.** This may range from 3-D multichannel seismic reflection for sites on accretionary prisms, Large Igneous Provinces (LIPs), or divergent margins (which may require a heretofore unprecedented commitment to such an advanced geophysical capability), to submersible and ROV seafloor mapping of prospective mid-ocean ridge sites.

- **Drilling, complete sampling, and related on-site experiments with one or more drilling platforms.** COMPOST-II acknowledges and reaffirms the multiple-platform vision embodied in both COMPOST-I's recommendations and the 1996 ODP LRP. Such an array of platform options, with overlapping capabilities, is critical for a successful approach to the drilling-related science envisioned by the U.S. earth sciences community.

- **Use of selected drillholes as "Earth windows."** COMPOST-II sees drilling of clean, stable holes as the critical step in establishing a global array of sites suitable for a vast assortment of possible scientific and technical uses, from downhole logging experiments to the construction of seafloor observatories for monitoring of active processes (e.g., fluid flow, seismicity) to testing of critical downhole technologies.

Over the past quarter century, the Deep Sea Drilling Project (DSDP) has evolved into ODP, but both programs have heretofore operated primarily as a series of leg-specific "projects." Some efforts have built constructively on past results (*e.g.*, Hole 504B for ocean lithosphere studies, paleoceanographic water-depth and latitudinal transects for assessments of past changes in global circulation and chemistry), while many others remain as stand-alone forays into diverse marine geologic environments. Ocean science has progressed from a period of reconnaissance during the opening days of DSDP, to the present, where sophisticated hypothesis-testing is more the norm than the exception. COMPOST-II urges that future planning for both facilities and funding in scientific ocean drilling accept a singular reality, which is driven by the science of interest to the U.S. community:

Drilling represents a "cascade" of activities (see figure), which encompasses complete predrilling characterization of important geologic environments and processes, continues with creation and attendant sampling of the boreholes themselves, and may go on for years beyond departure of the drilling platform or platforms to use such boreholes, and the cores that come from them, to answer important questions about Earth's evolution.

RECOMMENDATIONS

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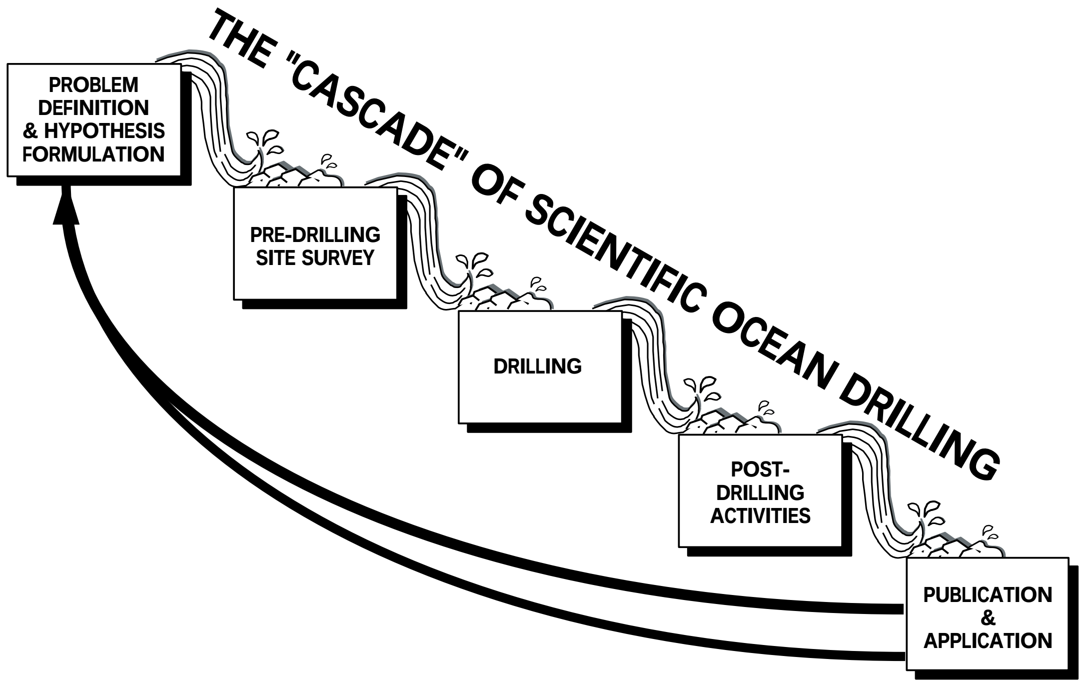

and geologic environments (e.g., overpressured sections); and
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SUPPORTING STATEMENTS OF U.S. SCIENTIFIC OBJECTIVES AND RELATIONSHIPS WITH POST-2003 SCIENTIFIC OCEAN DRILLING

EVOLUTION OF THE OCEAN/ ATMOSPHERE SYSTEM

OVERVIEW

A number of planning documents are now available that outline specific goals addressing fundamental ocean, atmosphere and climate problems that can be uniquely addressed by the study of the marine geologic record. These documents include the MESH Program Plan developed within the U.S. community and the IMAGES Program Plan developed by the an international pale-oceanographic program sponsored by IGBP/Pages and SCOR. These program plans were incorporated into the COMPOST-I document in 1993.

Since then, there has been progress towards these objectives through research activities funded through the Earth System History panel at NSF, and through continued progress within the ODP. In addition, paleoceanographic objectives within the U.S. were discussed and evaluated during the 1996 NSF-sponsored workshop which discussed future research objectives for the marine geology and geophysics community (FUMAGES).

The fundamental contributions to understanding earth system history that can be made through the study of the marine geologic record include:

- documenting the range of variability and sensitivity of the ocean-climate system;
- documenting the rates of change in the ocean-climate system;
- developing a better understanding of the mechanisms related to changes in the ocean climate system; and
- enhancing our confidence in numerical models that are used to investigate the sensitivity and response of the ocean-climate system to potential agents of change.

Given these “contributions” and progress in data collection and modeling experiments, it was possible for MESH and FUMAGES to formulate the following vision for paleoceanographic research:

In ten years, paleoceanographic research will be conducted utilizing an integrated strategy incorporating process models and data sets, with compatible spatial and temporal resolution, to resolve important couplings of the ocean-climate system and to more accurately assess processes responsible for past and future changes in climate.

Thus, within the context of a post-2003 drilling program, paleoceanographic experiments will be formulated to integrate climate, ocean and geochemical models of the earth system that pose hypotheses that can be tested with temporal and spatial sampling frameworks.

Given this vision of the future, the classic problems of paleoceanographic research identified by FUMAGES include understanding:

1) relationships between sea level, ice volume, and climate change;
2) interactions between atmospheric carbon dioxide, climate, and its biospheric and geospheric regulation;
3) long-term changes in ocean chemical composition and geochemical fluxes as related to geological and biological evolution;
4) solar and magnetic field variability, their role in climate change, and affect on cosmogenic nuclides; and
5) changes in modes of ocean circulation in relation to climate change and the evolution of oceanic basins.

While FUMAGES and MESH have separated their scientific objectives into different time-scale domains, it has become increasingly evident that this division is artificial. Recent progress has led to two important shifts in how climate is viewed that seem to cut across all time scales: 1) the growing realization that substantial changes in atmospheric CO_2 are likely to have played a large role in both long-term and short-term climate change, and 2) the discovery that nonlinear interactions in the ocean-climate system may have played a key role in determining the sensitivity of climate to both internal and external forcing. These nonlinear interactions can shift climatic variance to both higher and lower frequency oscillations. Thus, while a summary is presented below of the FUMAGES objectives which are distinguished in terms of temporal resolution, these problems must be considered within the context of the climate spectral continuum.

NEEDS

Ocean drilling will play a critical role in the establishment of the spatial arrays of high resolution, well-dated stratigraphies of ocean-climate proxies with the appropriate temporal resolution.

Spatial arrays of high-resolution time series will document the range of variability in the ocean-climate system and provide an understanding of the sequence of events as oscillations propagate through the system. The phasing and amplitudes of the responses provide key insights into the mechanisms and sensitivity of climate change and help establish the relative importance of tropical forcing and high latitude processes. For the different time-scales of variation, the climate signal will be recovered from different carriers. For understanding the climate oscillations on interannual to century time scales, records with annual resolution are needed, implying the use of annually-banded corals and varved sediments in marginal basins. For decadal to millennial time scales, high-sedimentation-rate deep-sea sediment drifts, continental rise, and marginal sediments add significantly greater geographic coverage of the oceans. Although sections with slower rates of accumulation are useful in determining the changes in the character of the ocean-climate system on the tectonic time scale, more rapidly accumulating sections are required to study the nature of the processes that effect these changes in those parts of the Cenozoic and Mesozoic with distinctly different climatic states and boundary conditions.

In addition to establishing global inventories of the important geochemical tracers, two key elements guide our sampling strategy: 1) sampling arrays are needed to document changes in key oceanographic processes with the appropriate time and spatial resolution, and 2) these arrays should be with integrated with process models. This integration requires that data sets have compatible spatial and temporal resolution to resolve important couplings of the ocean-climate system and to assess more accurately processes responsible for past and future changes in climate. Specifically, sampling arrays are needed:

- to document changes in thermohaline structure and circulation of the past ocean. Sampling and analysis are also needed to evaluate changes in chemical and temperature distribution of the deep ocean;
- to document changes in tropical temperatures, especially in non-upwelling regions of the oceans;

- to document changes in ocean production, as well as changes in surface pCO_2; and
- to document changes in surface ocean heat transport, especially in tropical regions and in boundary current regions.

Recovery of continuous, undisturbed sedimentary sequences is absolutely essential to the success of the research objectives stated above. Thus, hydraulic piston coring (APC), extended core barrel (XCB), and improved versions of those tools should be deployed until refusal. Likewise, for recovery of challenging lithologies, such as interbedded chert/chalk sequences, a Diamond Coring System (DCS) or suitable alternative will be required. Successful interpretation of primary geochemical signals requires that we not attempt to study diagenetically-altered sequences. At worst, such diagenetic overprints should be quantifiable so that they can be "removed."

While drilling will play a critical role in establishing the sampling arrays, significant pre- and post-cruise science will also be critical to the stated objectives. The necessary data sets will require analytically intensive efforts. Continuous real-time data analysis, using half- and full-core multitrack sensor arrays onboard ship, will be essential. In terms of a plethora of shorebased analyses, such as generation of stable isotope and other geochemical proxy data, presently available USSSP funding is, unfortunately, insufficient to support most of the required analyses. This places a hardship on investigators who are expected to generate the necessary data. Adequate funding for the post-cruise analytical component of high-resolution geochemical studies must therefore be considered a priority need.

LINKAGES: SUMMARY OF FUMAGES SCIENTIFIC OBJECTIVES

Millennial to interannual changes in climate

What is the cause, nature, and range of climate and ocean variability at the interannual to millennial time scale given that there is no obvious external forcing?

Key problems and scientific questions

1) What mechanisms force the climate-ocean system variability at these time scales?
2) How are climatic oscillations on these time scales transmitted through the ice-ocean-atmosphere system?
3) To what degree is the spectral character of these oscillations in climate stable over hundreds to thousands of years?
4) Do comparable oscillations occur under markedly different climatic regimes or under different boundary conditions?

Climate change on time scales from 10^4 to 10^5 years

What processes set the sensitivity of the climate system to external (orbital) forcing, and what processes are responsible for the long term evolution of this sensitivity?

Key problems and scientific questions

1) What is the role of the Arctic and Nordic Seas in triggering an ocean-climate response to insolation forcing?
2) What is the role of tropical temperatures in setting the response to insolation changes? Is there a tropical thermostat? Does it always work?
3) What role do atmospheric CO_2 variations play in setting the sensitivity of the ocean-climate system to external forcing?
4) What processes are responsible for the geographic and temporal pattern in phase relationships between the radiation forcing and the ocean-climate system response ?
5) How is the climate response that is forced directly by solar radiation related to higher and lower frequency responses of climate?
6) What causes the spectral character of the climatic response to orbital forcing to change with time?

Long-term evolution of global climate and ocean geochemistry

Why are there ice ages and greenhouse periods in Earth history?

Key problems and scientific questions

1) Can we better elucidate the record of Earth system variation on tectonic time scales using geochemical proxies for fundamental processes?
2) What are the fundamental causes of ocean-climate variability on tectonic time scales? Can we effectively explain the initiation of glacial regimes or the maintenance of low latitudinal thermal gradients in non-glacial episodes? Can variations in the mode of ocean/atmosphere heat transport alone result in fundamentally different climate regimes?
3) What was the biotic response to fundamental changes in the ocean/climate system, and what role did biogeochemical cycling play in longer-term climate evolution?

RIDGE: RIDGE INTER-DISCIPLINARY GLOBAL EXPERIMENTS

OVERVIEW

The goal of the RIDGE Initiative is to understand the complex and interrelated tectonic, magmatic, hydrothermal and biological processes involved in the formation of new oceanic crust and lithosphere. The major scientific problems RIDGE is addressing are embodied in 5 major "Program Elements":

1) **Global structure and fluxes** – to characterize the tectonic structure, geochemistry, biology and energy fluxes of the mid-ocean ridge on a global scale;

2) **Crustal accretion and segment-scale processes** – to assess the key variables affecting crustal accretion, and develop quantitative, testable models of mid-ocean ridge processes;

3) **Mantle flow and melt generation** – to constrain the nature of mantle flow and melt generation beneath oceanic spreading centers;

4) **Temporal variability of ridge crest phenomena** – a seafloor observatory program to understand the variability of active seafloor tectonic-volcanic-hydrothermal systems on time scales of days to decades; and

5) **Event detection and response** – to develop a reliable event detection and quick-response capability for identifying, locating, and characterizing transient ridge crest phenomena.

In addition, RIDGE embraces key "cross-cutting themes" which span several program elements. A prime example is biology, including both seafloor ridge-crest biology and the "subsurface biosphere." The international InterRidge Initiative shares many of these objectives.

Both RIDGE and InterRidge recognize the unique contributions that ODP can make towards achieving their goals. Drilling is viewed as one component of a broader, longer-term investigation of mid-ocean ridge processes that involves detailed surface mapping and sampling, geophysical experiments, and concurrent monitoring of tectonic, magmatic, and hydrothermal processes at selected seafloor observatory sites that ideally include instrumented ODP holes. In particular, drilling provides the only method of directly sampling the subseafloor components of active ridge crest magmatic, hydrothermal and biological systems. Ridge-crest drill holes will also provide the only means of installing instrumentation in the subsurface to monitor processes *in situ*. Drill cores, fluid samples, and *in situ* physical properties measured in ridge-crest holes will address critical questions such as:

- lithostratigraphy, composition, and alteration history of “zero-age” crust;
- porosity and permeability structure of the crust above an active crustal magma body;
- time/space variations in hydrology and fluid properties within an active axial hydrothermal system;
- feedback loops linking magmatic, hydrothermal, and tectonic systems at ridge crests; and
- evolution and role of the subsurface biosphere at ridge crests.

In the 1990’s, ODP has already made significant contributions to RIDGE by successfully drilling into large, polymetallic sulfide deposits at both the Mid-Atlantic Ridge (TAG) and the sedimented rift at Middle Valley, and by emplacing borehole observatories (CORKs) in Middle Valley hydrothermal systems. However, many long-standing top priorities for drilling at ridge crests remain to be fulfilled, largely because technological issues in establishing stable holes in very young oceanic crust remain under development.

The highest priorities for drilling at ridge crests include:

1) Drilling a deep hole (1-2 km) in “zero-age” crust, through the entire extrusive and sheeted-dike section to the top of an axial magma chamber;
2) Drilling arrays of shallower holes (100-500 m) into an active magma-hydrothermal system as part of a RIDGE observatory; and
3) Drilling through a large polymetallic sulfide deposit of an active hydrothermal system, into the underlying reaction zone 1-2 km beneath the seafloor.

All of these holes should be drilled with the intent of emplacing long-term instrumentation to monitor ridge-crest processes, as envisioned in the RIDGE seafloor observatory.

NEEDS

The long-term success of ridge-crest drilling depends critically on the development of new technology to establish stable holes in young, fractured rock, and to recover uncontaminated core, fluid and microbiological samples throughout the extrusive/intrusive section. Subsurface temperatures in ridge crest drilling may exceed 400°C, so drilling and sampling systems as well as long-term instrumentation must be hardened to withstand such conditions. If drilling “zero-age” crust at unsedimented ridges proves to be technically unfeasible, RIDGE drilling objectives should be addressed using more conventional technology at a sedimented ridge crest. It will be vital to coordinate ridge-crest drilling closely with both RIDGE and InterRidge programs.

DRILLING INTO THE OCEANIC LITHOSPHERE

OVERVIEW

A joint InterRidge, IAVCEI, USSSP conference, "Ocean Lithosphere Drilling into the 21st Century," held at Woods Hole in May 1996, identified the following drilling-related objectives: 1) to understand the physical and seismic structure of ocean crust at both slow- and fast-spreading ridge systems, as well as their magmatic, structural, hydrological and metamorphic history; 2) to understand the significance of Mesozoic emplacement of Large Igneous Provinces (LIPs) in the Pacific and Indian Oceans; 3) to understand the hydrothermal processes active at young ridges and in arc systems, and their role in the genesis of metallogenic minerals; 4) to establish observatories for long-term seismic and geophysical monitoring; 5) to determine the composition of ocean crust at subduction zones; 6) to understand the origin of magnetic anomalies; and 7) to test the forearc hypothesis of formation of some important ophiolites. The first two objectives were the highest priorities of the conference.

Strategy

The general strategy recommended by the conference is a combination of very deep drilling to Moho in fast-spread crust, offset-section drilling into exposures of the oceanic lower crust and upper mantle, and the drilling of oceanic plateaus and in island arcs. The most ambitious of these is Moho penetration in fast-spread crust in the Pacific. Deep drilling (to 2-3 km) was recommended to understand crustal structure and ridge segmentation at a slowly-spreading ridge in the North Atlantic, as was a continuation of study of the lower ocean crust and upper mantle by offset-section drilling. The conference also endorsed initiatives for drilling of LIPs, island arcs, young ridges, and hydrothermal systems hosted by high-silica lavas in arc systems. Meeting participants reiterated the long-expressed objective of establishing a long-term observatory on the axis of an active ridge.

Readiness

Drilling Mohole will require site assessment using surveys and some drilling during 1998 to 2003. An exploratory drilling leg is essential. It may be possible to use existing surveys to identify drilling targets for segment studies in the North Atlantic, but site-specific near-bottom studies may be necessary for precisely placing drill sites. Preliminary drilling of short holes is necessary at LIPs to determine their age relationships, before targeting deeper holes. There are places where legs devoted to hydrological and hydrothermal processes on ridges/island arcs can be drilled after additional surveying.

NEEDS

The conference endorsed having two drillships for lithospheric objectives. Improving core recovery, drilling rates, and total penetration are all important. Present ODP initiatives to improve dynamic positioning and heave compensation were strongly endorsed. The capability of spudding holes readily on young ridges, in active hydrothermal systems, and on sloping fault surfaces is required. The routine ability to set multitiered casing is a prerequisite for drilling more than ~2-2.5 km into the ocean crust. A Mohole to 6-7 km below the seafloor will require a riser.

LINKAGES

Most of this work can be coordinated with InterRidge. Linkages to the MARGINS Initiative should also be established to plan drilling of any deep hole in a forearc plateau, and in arc-based hydrothermal systems. IAVCEI is the link to LIPs. Many of these holes will also be of interest to the subsurface biosphere community.

GEOMAGNETISM AND OCEAN DRILLING

OVERVIEW

One of the principal scientific objectives of deep-sea drilling at the dawn of the plate tectonics revolution in earth sciences was to test the progression of ocean floor ages that was predicted from the marine magnetic anomaly time scale of geomagnetic polarity reversals. In the ensuing nearly 30 years of ocean drilling under DSDP, IPOD, and ODP, geomagnetism has continued to provide hypotheses of global significance and has contributed to the solution of specific problems in many other disciplines that require data from the oceans. An understanding of the Earth's magnetic field and its variation with time is specifically cited in one of the top priority research themes in the recent "Wyllie report." Moreover, the application of paleomagnetism as a tool for global correlation and tectonic analysis is also relevant to several other research themes.

Some examples of established geomagnetism and paleomagnetism objectives in ocean drilling that still remain generally valid include age calibration of the geomagnetic polarity time scale and its use in global correlations, determining the paleolatitudinal history of oceanic plates to allow separation of apparent and true polar wander, delineating the source of marine magnetic anomalies in the oceanic crust, and developing reliable ocean climate proxies based on environmentally-sensitive magnetic properties of sediments. These and other paleomagnetic objectives, as well as an evaluation of capabilities needed to address them in ODP, were discussed in a JOI/USSAC-sponsored workshop in 1986 (K. Verosub, M. Steiner, and N. Opdyke, conveners).

More recently, a JOI/USSAC-sponsored workshop held in 1994 (B. Clement, convener) has identified global mapping of paleosecular variation in general, and field behavior during a polarity reversal in particular, as important geomagnetic objectives for ODP and any successor ocean drilling program. On a related front, a JOI/USSAC-RIDGE-NSF/OCE-sponsored workshop held in October 1996 on magnetization of the ocean floor (H.P. Johnson and D. Kent, conveners) has identified the origin of both short-term and long-term variations in anomaly amplitudes as important problems that need to be resolved. Charting the full temporal spectrum of variations in paleointensity, which may be reflected in anomaly amplitudes as well as in sedimentary records, can thus be considered an integral part of the geomagnetism research agenda that requires ocean drilling.

NEEDS

The history of reversals determined from oceanic magnetic anomalies and sediment magnetostratigraphies has already revolutionized our understanding of the Earth. Reversals in polarity are the biggest signal from the core dynamo. Obtaining a reliable description of the morphology of the field as it evolves from one polarity state to the other will thus be essential to an understanding of the dynamo generation mechanism. Observations from a global distribution of sites are needed to characterize fully the complicated spatial variations that occur over the few thousand years that a polarity reversal takes place. Accordingly, long, undisturbed high-resolution sediment sections that can uniquely be obtained from a *JOIDES Resolution*-type platform will be a critical source of polarity-transition studies. There are similar requirements for the mapping of paleosecular variation, especially in relative paleointensity, during full-polarity intervals. In both types of studies, it will be important to reduce greatly the amount of magnetic contamination from coring. The ocean drilling requirements to study the evolution of Earth's magnetic field are otherwise consonant with those for studies of the evolution of the ocean/atmosphere system. The very recent emergence of realistic 3-D supercomputer models of the geodynamo will provide unprecedented opportunities for making and testing predictions. Further advances in dynamo modeling are expected from initiatives such as CSEDI.

In addition to providing a record of field reversals, marine magnetic anomalies also contain information on both short- (10^4 to 10^5 year) and long-term (~10^7) variations in paleointensity, a very poorly documented yet fundamental property of the geomagnetic field. Exploitation of this potential paleointensity record, however, will require a more exact understanding of the source of marine magnetic anomalies in the oceanic crust. Direct and continuous sampling of oceanic crustal sections that are representative of fast spreading ridge systems are required to profile the relative magnetic contribution of the principal crustal layers and to understand the origin of their magnetizations. This will involve obtaining samples from many holes that penetrate all of Layer 2A, the likely source of the short-term anomaly variations, in the context of a few well-chosen sites that allow the magnetic characterization of all of the main rock types in the oceanic crust. The combination of high core recovery and modest- to deep-penetration into the oceanic crust will require drilling capabilities not currently available on the *JOIDES Resolution*.

MARGINS INITIATIVE

OVERVIEW

Scientific objectives and strategies of the MARGINS Initiative have been developed over the last nine years. They are the result of five workshops attended collectively by more than 150 scientists and the coordination efforts of a Science Committee. Workshop reports and an Initial Science Plan are now generally available (on the web at http://zephyr.rice.edu/margins, or by mail from the Margins Planning Office, Department of Geology and Geophysics, Rice University, MS-126, 6100 Main St., Houston, TX 77005). In terms of the interactions between MARGINS and ocean drilling post-2003, statements below probably reflect the desires of an even broader continental margins community than has been directly involved in MARGINS planning to date.

Scientific objectives

1) **To understand the low-strength paradox of lithospheric deformation.** Very large faults accommodate a major component of strain at continental margins, yet these structures move at shear stresses far lower than those expected from laboratory and theoretical studies. Fluids are likely to play a role, but a viable theory for how fluids affect fault movement does not exist. A larger problem is that extant models of lithospheric strength predict that lithosphere is too strong to be deformed by known tectonic stresses, yet such deformation clearly takes place.

2) **To understand the nature of strain partitioning during deformation.** Vertical and horizontal partitioning of strain in the crust and upper mantle during deformation are not the same as the distribution of surface strain, but existing models of crust and upper mantle rheology remain largely conjectural.

3) **To understand magma genesis and recycling.** While models of mantle flow and magma genesis at mid-ocean ridges have advanced considerably, similar models in margins settings have not moved beyond kinematics and provide only crude predictions of magma distribution. New questions have also been raised about the role of magmatism in the construction of continental crust.

4) **To explore the relationships between stratigraphic preservation and geological events.** Continental margins are the Earth's principal loci of sedimentary accumulations and provide one of the best preserved records of global sea-level variations, climatic fluctuations, lithospheric deformation, ocean circulation, geochemical cycles, organic productivity, and sediment supply. Margins are also where most of the world's oil and gas reserves and hard mineral deposits are concentrated. Nonetheless, the processes by which physical interactions operative on small spatial and temporal scales ("event stratigraphy") are incorporated into the preserved stratigraphic record remain poorly understood.

5) **To investigate fluid fluxes and their effects on continental margin evolution.** Fluids play a ubiquitous, poorly understood, yet undeniably important role in all of the major margin-forming and deforming processes described above.

Strategies and implementation

The MARGINS Initiative proposes to address its scientific goals by:

- focusing on active systems;
- developing multidisciplinary case studies;
- studying whole systems;

- establishing scaling relations;
- integrating observational, laboratory, and theoretical modeling approaches;
- including comparative global analyses; and
- establishing event response strategies.

To implement the above, the MARGINS Science Committee has identified four high-priority case investigations:

1) **Seismogenic Zone Experiment.** SEIZE will be a multidisciplinary study of the seismogenic zone at a selected subduction margin. Critical observational methods will include 3-D seismic reflection profiling, passive seismic monitoring and tomography, and ocean drilling using the existing capability and a riser-equipped, deep-drilling vessel to be designed and constructed.

2) **Subduction Factory.** This experiment will take a comprehensive look at the cycling of materials through a subducting margin. Observations will focus on the incoming plate, fore-arc, subducting slab, mantle wedge, and volcanic arc. A wide variety of methods will be employed, including ocean drilling using the existing capability and, eventually, a riser-equipped vessel for deeper drilling into potentially overpressured zones.

3) **Rupturing Continental Lithosphere and the Birth of an Ocean.** This study will examine strain partitioning and fault dynamics where rifting and the formation of new oceanic lithosphere are propagating into a continent. Tools to be used include 3- and 4-D seismic reflection data acquisition and analysis and the full suite of available and future ocean drilling technologies.

4) **Sediment Dynamics and Continental Margin Strata Formation.** This study is designed to clarify the scaling relationships among physical processes, the formation of sedimentary signatures, and preservation of the longer-term stratigraphic record. The overall goal is to determine the timing, spatial distribution, and causes of stratal discontinuities in terms of depositional and erosional processes, and to evaluate the importance of eustasy, sediment supply, climate, tectonics, and physiography in their formation. Such an investigation will likely be carried out in the vicinity of one or more of the focussed studies identified above.

NEEDS

1) All proposed MARGINS studies require the continuing availability of a *JOIDES Resolution*-type drillship. The Science Committee looks at such a capability as an essential part of investigating continental margins. Drilling is not the capstone of these research efforts, but one of many tools used in concert to solve MARGINS objectives.

2) Each study would also benefit from the availability post-2003 of a riser-equipped vessel capable of drilling deep holes. Such drilling, through potentially active faults and seismogenic zones, requires the capability to stabilize the hole and effectively remove

cuttings by circulating drilling mud; riser capability (with or without blowout prevention) is essential.

3) MARGINS studies require systematic acquisition of 3-D multichannel seismic reflection data. These data are essential in their own right for imaging the complex tectonics of these environments, but are also important for providing site-survey databases crucial for planning operations of a riser-equipped drilling vessel.

4) MARGINS studies also require the use of clean, stable drill holes for emplacement of seafloor observatories, for global seismicity and fluid flow monitoring, borehole fluid sampling, *in situ* temperature and pressure measurements, and many other objectives.

5) MARGINS experiments to study sea-level change and various other responses of margin sedimentary systems to forcing functions absolutely require the use of alternate drilling platforms, possibly jack-up rigs, to drill in shallow water environments where neither the *JOIDES Resolution* nor the envisioned riser-equipped vessel can operate.

LINKAGES

1) Continental margin science can benefit substantially from increased cooperation with the petroleum industry, perhaps most by gaining access to extensive industry seismic datasets. In exchange, the scientific ocean drilling community should be willing to allow cooperating companies access to the planning and execution of drilling science.

2) Continental margin science can also benefit from increased cooperation with the international Continental Scientific Drilling Program. Scientific objectives of planned continental drilling, such as the San Andreas Drilling Project, are identical to those MARGINS proposes to address in the water-covered domain. Each environment, land and marine, offers specific scientific, technological and cost advantages that could be more effectively exploited.

3) MARGINS proposes projects which are fundamentally multidisciplinary, but depend on the availability of ocean drilling. The experimental approach is one that places ocean drilling, not as an isolated data acquisition event, but as an integral part of a strategy of pre- and post-drilling science, all of which are essential to success in solving important continental margin objectives.

POST-DRILLING OBSERVATIONS AND EXPERIMENTS

OVERVIEW

Scientific objectives

Characterization of large portions of the Earth's interior and delineation of active processes localized within sediments or oceanic crust require long-term deployment of instruments in boreholes and/or active experiments that are conducted after the effects of drilling have dissipated. As the recurrence intervals of seismic events, pore water flow, thermal and chemical advection, slope failure, and volcanic eruptions range from seconds to decades, the fundamental nature and variability of our inner planet, of plate tectonics, and of biogeochemical fluxes between crust and the ocean can only be defined by time-series observations.

Specifically, we seek to:

- establish the mantle and crustal properties and dynamics that create new oceanic crust at spreading centers and consume old lithosphere in subduction zones, that control the distribution of hot spots, and maintain the Earth's magnetic field;
- delineate the mechanisms that drive fluid flow through oceanic crust and sediments in different tectonic settings, and the variability of that flow;
- relate flow to the mechanical properties of the crust and sediments, local and regional stress fields, thermal flux, and phase changes of components involved in fluid migration;
- determine how fluid and mechanical properties relate to earthquake occurrence at plate margins; and
- define the cycle of geochemical species through oceanic lithosphere by pore fluid advection, and the relationship of those elemental fluxes to global mass balances in the hydrosphere, atmosphere, and biosphere.

Priorities and strategies

Specific scientific priorities that can be addressed by post-drilling instrumentation and experimentation in boreholes are detailed in national workshop reports on broadband seismology from the Ocean Seismic Network (OSN), use of drillholes for observatories (BOREHOLE), ridge-crest observatories at the Juan de Fuca Ridge (RIDGE), and use of existing submarine cables in support of seafloor instrumentation. Additional experiments are delineated by international programs on seafloor observatories (ION) and ridge-crest observatories (InterRidge).

A coordinated U.S. Seafloor Observatory Program (USSOP) has been proposed that will support coordinated engineering, guide development of major shared facilities on the seafloor, and assign priorities to individual experiments. A close working relationship between ODP engineering and USSOP needs to be developed to bring observatories fully into the drilling program.

Readiness

Post-drilling experiments in boreholes have already begun. Past studies include: submersible-based downhole logging for temperature, fluid flow rates, borehole geometry and structural elements, fluid sampling, 2-3 year monitoring programs of subseafloor fluid pressure and temperature at several active lithospheric plate margins (with the development of instrumented borehole seals, CORKs), and associated *in situ* hydrogeologic tests to define the nature and magnitude of fluid advection. Current studies involve a hole-to-hole experiment to establish hydraulic conductivity and fluid storage capacity of shallow oceanic crust, an active test of fault mechanisms by induction of a short-term pressure anomaly within a sealed borehole while monitoring local microseismicity with OBSs, and a pilot experiment to emplace a broadband seismometer in a crustal borehole. Additional experiments have been proposed but await funding and engineering development.

NEEDS

A primary need for post-drilling science is the ability to revisit observatories independent of the drilling vessel to download data, conduct active tests, exchange power supplies, swap out instruments, or collect samples. These activities require use of a submersible, a ROV, or wireline reentry. ODP and its successors must consider use and support of auxiliary vessels that carry these maintenance tools.

Some additional needs relate to development of technology common to any seafloor installation (power, telemetry, real-time control, sensors, etc.), but some requirements are unique to borehole installations. Some sensors will have to extend through (or be mounted on the outside of) the casing; some instruments must be coupled to the surrounding rock or extend beyond drilling disturbance, and will require special installation procedures; instruments in many holes will have to be vertically isolated (packed off) from other sections of the same hole for the duration of the experiment (years).

LINKAGES

The observatories and experiments described here are integral to tectonic, biogeochemical, and seismic studies proposed by communities represented by RIDGE, MARGINS, OSN, and BOREHOLE.

RELATIONSHIP TO CONTINENTAL DRILLING

OVERVIEW

A wide range of nearly identical fundamental scientific questions requires drilling on both continents and oceans and motivates a continuum of research endeavors on both land and at sea. Such questions range from the physical and chemical processes responsible for earthquakes and volcanism to the processes responsible for changes of Earth's climate. The report entitled "Scientific Rationale for Establishment of an International Program of Continental Scientific Drilling," prepared by the Coordinating Committee for Continental Drilling of the International Lithosphere Program, calls for the establishment of an International Continental Drilling Program (ICDP) that would by complementary to ODP.

Along with the similarities of the scientific objectives of both continental and oceanic drilling, common requirements for engineering and technical support, and common needs for both core and data repositories and committee structures for scientific review and prioritization, all suggest that promoting close working relationships between programs of ocean and continental scientific drilling will be beneficial to all concerned.

EDUCATION AND OUTREACH PROGRAMS

OVERVIEW

Education-based activities in scientific ocean drilling are important for fostering a science-supportive public, as well as for attracting the best and brightest students to pursue further studies in problems of integrated earth systems. Drilling-related activities are significant investments toward a better understanding of earth processes by students of all ages. To this end, JOI should continue to develop the following educational programs related to fundamental scientific and technological objectives:

1) **CD ROM and Web based activities aimed primarily at K-12 and undergraduate curriculum enrichment, available to instructors at little or no charge.** A variety of educational materials based on ODP scientific and technological advances should continue to be provided to teachers and students through CD ROM development. The previously released CD entitled “ODP: From Mountains to Monsoons” has proved to be an important learning tool because of it’s creative and innovative structure in teaching integrated science, and because it is available free of charge. The proposed “Gateways to Glaciation” CD will provide a different perspective of the integral nature of ODP science and should also be distributed at little or no charge. Additional CD ROM activities should be considered along the thematic lines of the existing ODP LRP.

   Further advancements aimed at wider use of internet capabilities utilizing the World Wide Web (WWW) need to be pursued. The existing JOI site is well organized and accessible for the informed scientist, but needs to be reconsidered in terms of ease of public access as well. To reach the public effectively, the site needs to be linked more broadly than it has been in the past. Subject-specific WWW search engines should succeed in locating ODP or known, related entities like JOI. The program must remain committed to educational information dissemination utilizing evolving, popular electronic technologies.

2) **Distinguished lecturers series.** The JOI/USSAC Distinguished Lecturer Series has proven successful in making ODP scientific results more readily available to academic institutions and other scientific organizations not already intimately linked with ODP. The series is designed to bring the results of ODP research to students at both the undergraduate and graduate levels and to the earth science community in general. This is important not only for maintaining support and enthusiasm for ODP, but also for encouraging “new blood” to become involved in scientific ocean drilling. The series honors both ODP and the individuals who have made significant contributions and should be continued at or above present levels post-2003.

3) **Fellowships for outstanding masters and doctoral candidates.** The primary objective of the Ocean Drilling Fellowship Program administered by JOI/USSAC has been to provide pre-doctoral scientists of unusual promise and ability with opportunities for research on problems, largely of their own choice, that are compatible with the research interests of ODP.

Because research may be directed either toward the objectives of a specific ODP leg or to broader themes, the Fellowship Program contributes to the overall ODP research effort in a significant way. JOI/USSAC Fellows to date have been very productive in terms of their research and contributions to the scientific community. The program should be continued at or above the present levels post-2003, with the recognition that changing demographics of graduate study and employment opportunities require the inclusion of exceptional masters students in future fellowship competitions, and that industry (petroleum, materials design and fabrication, environmental monitoring) partnerships should be actively sought in the creation of more fellowship opportunities in the future.

Scientific partnerships with industry

Overview

Objective

Develop potential for industry/academic partnerships in scientific ocean drilling.

State of the industry

A cautious state of optimism currently exists in the petroleum industry. Cost-cutting improvements in efficiency and new technological developments are enabling the industry to operate at costs much lower than predicted five years ago. Several factors have combined to enable the increased activity:

- increasing world energy demand;
- an upturn in hydrocarbon prices;
- availability of international opportunities with favorable investment terms; and
- technological advances.

Strategy

Education on the value of scientific ocean drilling to the petroleum industry in particular is critical to the development of any partnership. A useful first step would be to build on existing ODP ties with industry, whether specifically associated with drilling or with individual U.S. academic institutions. Potential interactions with the petroleum industry could also cover many different disciplines. Therefore, scientific ocean drilling should concentrate on developing project-specific partnerships with individual companies and industry sectors.

Developing partnerships with the petroleum industry should focus on two disciplinary areas:

- contributions to educational programs directly supporting graduate students, as well as indirect efforts to increase awareness of the earth sciences to younger audiences. Support for students helps grow the population of educated students for future employment within the petroleum industry; and
- direct participation in future drilling programs through the following efforts:
  - direct funding of scientific ocean drilling-related activities;
  - data exchange for site augmentation, drill site design and strategies, etc.; and
  - partnerships in the development and testing of new technologies.

Needs

JOI should convene a committee of industry representatives interested in developing a mutually constructive relationship with ODP. That group, different from the JOIDES TEDCOM, should be charged with developing a strategy on potential industry partnerships. This group could concentrate on providing communications links for establishing pertinent dialogues with different sectors of the petroleum industry, well in advance of the transition to a post-2003, multiple-platform drilling program. Although the focus should be on the petroleum industry, efforts to involve other related industries (e.g., mining, computing, communications, etc.) are also critical to the development of healthy partnerships between commercial concerns and scientific ocean drilling.

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