JOIDES Journal

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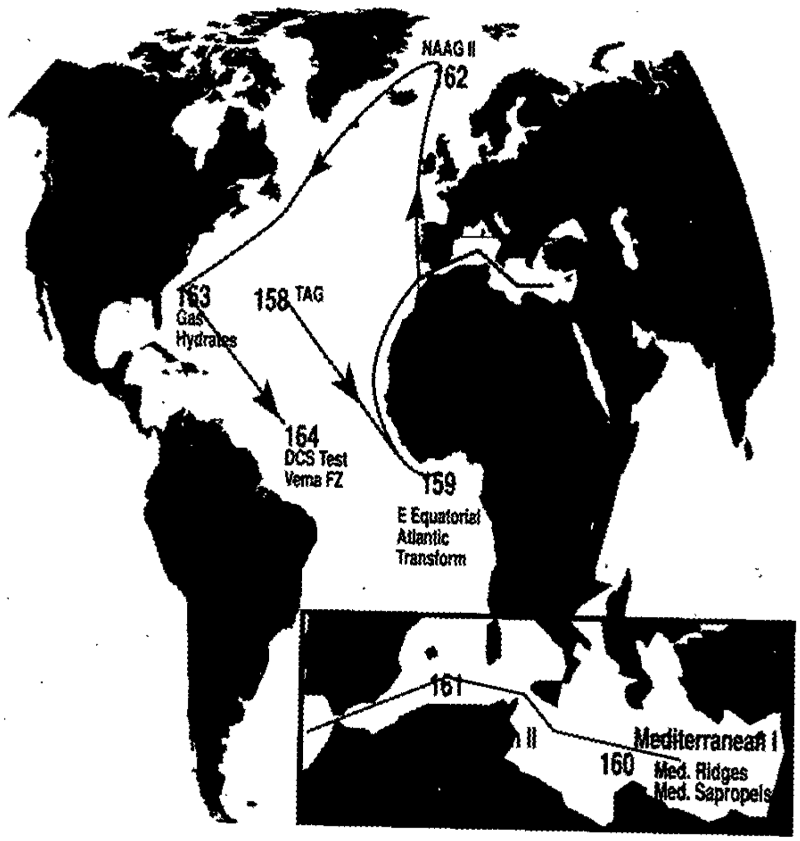

The Ocean Drilling Program Embarks on the 1995 Science Plan

Cover: Ship track of the *JOIDES Resolution* for legs scheduled in the FY95 Science Plan. In April, the JOIDES Planning Committee finalized objectives for seven legs of drilling for the Ocean Drilling Program. The planned legs will be located in areas ranging from the equatorial Atlantic to the Arctic Ocean. Specific objectives of the legs include characterizing: ridge-crest hydrothermal systems; the nature of tectonism at transform and collisional margin settings; Arctic glaciation, and gas hydrates.

The FY95 Science Plan begins with Leg 158 drilling at TAG. Drilling at TAG will investigate ridge-crest hydrothermal systems (see the Leg 158 Prospectus on page 2). The drilling and logging program at TAG will attempt to characterize the fluid flow, geochemical fluxes, and associated alternation and mineralization of an active hydrothermal system on a slow-spreading ridge. The leg runs from September 28 to November 23, 1994, at the TAG hydrothermal mound at 26°N on the Mid-Atlantic Ridge.

Cover graphic by Bill Collins, JOIDES Office.

The *JOIDES Journal* is edited by the staff of the JOIDES Office. Comments, suggestions and contributions for the content of the *JOIDES Journal* should be directed to:

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ODP Open Discussion Bulletin Board

The ODP LISTSERVER is a discussion bulletin board service to which individuals subscribe via Internet. It permits exchange of information among all subscribers. Currently the list administrator, Linda Weatherford, sends a report of the previous week's shipboard scientific and operations activities to all subscribers. Site summaries are distributed as soon as they are received at ODP from the ship. Periodically, an updated cruise schedule and brief descriptions of upcoming cruises are sent out. Any subscriber may send files to the list administrator for distribution. A file sent to the list address will be reviewed before being distributed. Anyone with an Internet address can subscribe. At present there are subscribers in the US, Canada, Europe, Australia and Japan. There is no charge for subscribing to the listserver.

To subscribe, send a brief message to Linda Weatherford (Weatherford@nelson.tamu.edu) requesting that you be added to the ODP-L subscription list.

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As of October 1, 1994, the JOIDES Office moves to the University of Wales, Cardiff. This is the first time that the JOIDES Office has been hosted by a non-US partner. The University of Washington JOIDES Office will close on September 30, 1994, and sends its best wishes to the Cardiff JOIDES Office—Rob Kidd, PCOM Chair; Colin Jacobs, Science Coordinator; Katherine Ellins, US Liaison; and Julie Harris, Office Coordinator.

After September 30th, please send all correspondence to the JOIDES Office at:

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JOIDES Journal

Joint Oceanographic Institutions for Deep Earth Sampling

University of California, San Diego, Scripps Institution of Oceanography

Canada-Australia Consortium

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European Science Foundation: Belgium, Denmark, Finland, Greece, Iceland, Italy, The Netherlands, Norway, Spain, Sweden, Switzerland, and Turkey

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Japan: Ocean Research Institute, University of Tokyo

University of Miami, Rosenstiel School of Marine and Atmospheric Science

Oregon State University, College of Oceanic and Atmospheric Sciences

University of Rhode Island, Graduate School of Oceanography

Texas A&M University, College of Geosciences and Maritime Studies

University of Texas at Austin, Institute for Geophysics

United Kingdom: Natural Environment Research Council

University of Washington, College of Ocean and Fishery Sciences

Woods Hole Oceanographic Institution

Focus

Brian Lewis
Planning Committee Chair

When you are busy having fun time flies. It is very difficult to appreciate that two years have gone by since the JOIDES Office moved to Seattle and that this is the last issue of the *JOIDES Journal* from this office.

This issue of the *JOIDES Journal* is devoted to the presentation of the revised White Papers from three of the JOIDES Thematic Panels: OHP, LITHP and SGPP. The TECP White Paper will appear in the next issue of the *JOIDES Journal*. These White Papers were prepared in response to a request from PCOM so that they could be used in formulating a revised *Long Range Plan* which PCOM is currently preparing. Please take the time to read through them as they will guide our scientific direction of for the foreseeable future.

The revised *Long Range Plan* will also incorporate feedback from other international and national programs (e.g., InterRidge) and partner countries. The *Long Range Plan* will be our vision for the next decade. It will also be used as the basis for renewal of the Program for the 1998-2003 time period.

In addition, this issue includes the final report from the Shallow Water Drilling Working Group. This group was tasked with establishing guidelines for surveys to support drilling at sites in less than 200 meters of water. The purpose of the guidelines are to ensure that drilling operations are safe from hazards related to shallow gas. Funding for these surveys is the responsibility of proponents while responsibility for quality control and interpretation lies with the Science Operator.

I view the outlook for the future in a very positive fashion, for the following reasons:

- ODP is reconciling the imbalance between realized financial support and program goals. Although some painful adjustment will be required we will be assured of a well-defined program through 1998.
- Great opportunities are being presented to us. These opportunities—if we grab them—will allow our drilling program to achieve many of its long range visions. The principal opportunity is the offer from Japan to build a riser-equipped drilling vessel. Coupled with an improved platform for non-riser drilling, this will finally allow deep penetration of margins and oceanic crust.

Improved understanding of the history of the Earth, achieved through scientific ocean drilling, will allow mankind to better deal with its own impact on our planet as well as improved ability to evaluate hazards associated with plate tectonic processes and provide guidance for resource evaluation.

Operating the JOIDES Office has been great because of because the ODP community has been focused and cooperative. I've also enjoyed our team effort at the office. Karen, with Bill's help and done a terrific job of producing the *JOIDES Journal*. I wish them and Sam—who many have communicated with in more than one language—all the best in the future. I also sincerely wish the next JOIDES Office at the University of Wales, Cardiff in the UK smooth sailing throughout their tenure.

Science Operator Prospectus Leg 158

TAG Hydrothermal System

Dr. Peter Herzig — Co-Chief Scientist
Dr. Susan Humphris — Co-Chief Scientist
Dr. Laura Stokking — ODP Staff Scientist

A complete Scientific Prospectus *for this leg is available from ODP, Texas A & M University, 1000 Discovery Drive, College Station, TX 77845-9547*

Abstract

The overall scientific objectives of Leg 158 are to investigate the fluid flow; geochemical fluxes and associated alteration and mineralization; microbiological processes; and the subsurface nature of an active hydrothermal system on a slow-spreading, sediment-free ridge. The active mound within the Trans-Atlantic Geotraverse (TAG) hydrothermal field at 26°N latitude on the Mid-Atlantic Ridge (MAR) is a large, mature deposit of varying mineralogy with emanating fluids displaying a wide range of temperatures and two distinct, but related, chemistries. The large size and age argue for a reasonably large and altered crustal root zone suitable for good drill penetration and recovery with conventional drill bits. Studies of this feature will give insight into fluid flow, structure, and "zone-refining" in active hydrothermal systems, and clarify how large, massive sulfide deposits, similar in size to those mined on land today, are formed on the modern seafloor. A transect of three holes (plus one alternate, but lower priority hole) is proposed to investigate the nature of fluids, deposits, and altered crust in the near-surface part of the hydrothermal system. At least one hole will penetrate into the stockwork zone underlying the surface deposit. Although it is anticipated that these objectives can be achieved with the currently available technology in this hostile environment, the nearby inactive *Alvin* and *Mir* zones are proposed as back-up drilling sites. Drilling at TAG will directly address the processes occurring during hydrothermal circulation. Understanding these processes, and the implications for energy transfer, geochemical fluxes, and the formation of ore deposits, are of fundamental importance to our knowledge of crustal accretion.

Introduction

Ridge-crest hydrothermal systems play a fundamental role in transferring a large fraction of the heat from the Earth's interior to its surface. Through thermally-induced flow of seawater in fractures and fissures in the permeable portion of the crust and upper mantle, much of the mantle-derived thermal energy is dissipated into the lithosphere, hydrosphere, and biosphere along the mid-ocean ridges. This circulation gives rise to a complex series of physical, chemical, and biological interactions that affect the composition of both seawater and the oceanic crust, and lead to the creation of many types of seafloor ore deposits, and to the existence of unusual biological communities.

Only drilling an active system on a mid-ocean ridge can clarify: (1) the permeability, pressure, and temperature structure within the upflow zone beneath an active hydrothermal system, (2) the nature of the chemical reactions between water and rock in both the upflow zone and the underlying reaction zone, (3) the mechanisms of sulfide precipitation and subsequent modification below the seafloor, (4) the structural control on the plumbing system within both the upflow and reaction zones, and (5) the evolution of major black smoker systems.

To date, attempts to answer such questions have relied upon the chemistry of waters from active vents, samples collected from surface outcrops, experimental and theoretical analyses of basalt/seawater systems, and observations of fossil systems in ophiolites. However, interpretation of these data requires that assumptions be made about the conditions which are present in the sub-seafloor part of an active system, sometimes about which rocks are in equilibrium with which fluids, and sometimes about the nature of the physical structure of an active system. Drilling a major, sediment-free black smoker system will provide the necessary evidence to discriminate between the models that have been put forward.

Hydrothermal systems on unsedimented ridge axes dominate global hydrothermal activity, and hence are an important contributor to global mass and energy fluxes. Drilling a mature, large volcanic-hosted deposit such as the TAG mound will clarify the processes of recrystallization and "zone-refining," the distribution of

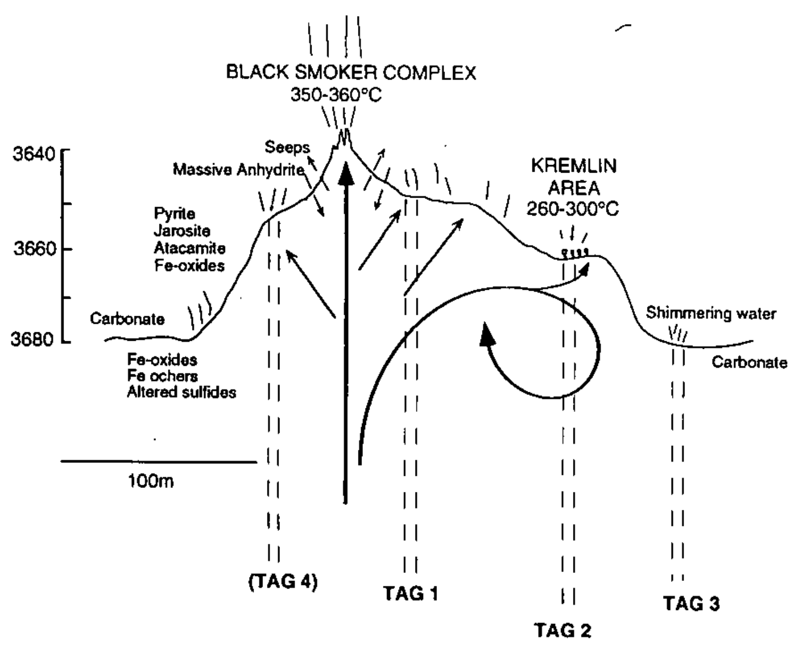

Figure 1. Schematic cross section of the active TAG hydrothermal mound derived from submersible observations showing the relative positions of the holes to be drilled during Leg 158. The fluid flow pattern within the mound is determined from the mineralogy of the deposits and the fluid chemistry. (Adapted from Tivey et al., 1994.)

minerals, the hydrothermal circulation and plumbing, the nature of the root zone, and the processes occurring during ore formation and deposition.

The TAG area has many features that make it the prime target for drilling an active volcanic-hosted hydrothermal deposit. Firstly, it is located in a slow-spreading environment, a major characteristic of the global rift system. The hydrothermal field is situated in the central part of a ridge segment bounded by small non-transform offsets or axial discontinuities, typical of many such segments on slow-spreading ridges. The active mound represents a good drill target, as the combination of size and maturity argues for a large surface areal target, with a well-developed root zone. The presently active mound is approximately 200 m in diameter and 50 m in height. It is composed of massive sulfides probably well in excess of 5 x 10^6 tons, being equivalent in size to some of the deposits in the Cyprus, Oman, and other ophiolites.

Geologic and Tectonic Setting of the TAG Hydrothermal Field

The ridge segment along which the TAG hydrothermal field is located is about 40 km long, trends north-northeasterly, and is bounded by non-transform discontinuities to the south and north at 25°55'N and 26°17'N, respectively. Seafloor spreading has been asymmetric over the last 10 Ma; half spreading rates are 13 mm/yr to the east and 11 mm/yr to the west.

Hydrothermal activity in the TAG field is located along a section of the eastern wall of the median valley. The TAG hydrothermal field consists of presently active low- and high-temperature zones, as well as a number of relict deposits. The zone of low-temperature activity occurs between 2400- and 3100-m depth on the east wall. The metalliferous deposits of this low-temperature zone include widespread surficial metal-rich staining of carbonate ooze, as well as discrete, massive layered deposits of manganese oxide, iron oxide, and iron silicate. The hydrothermal deposits in this low-temperature field exhibit a linear distribution along fault zones, trending sub-parallel to the valley floor, that are inferred to focus hydrothermal discharge.

The presently active black-smoker system occurs at the juncture between the rift-valley floor and the east wall at a depth of 3620-3700 m and at approximately 26°08'N, 44°49'W. The low-temperature field described above lies 3.7 km upslope to the east; the bathymetric axis of the rift valley is 1.5 km to the west. The active high-temperature field lies on oceanic crust that is at least 100,000 years old, on the basis of the present seafloor-spreading rate. Sediment thickness around the active mound is variable depending on the local morphology.

The black smokers are located on top of an elliptical mound surrounded by an apron dominated by carbonate ooze and metalliferous sediment that is about 500 m in diameter. The mound is about 200 m in diameter and rises about 50 m from a depth of 3670 m (Figure 1). It is composed of massive sulfides, with distinct sample types being distributed from the interior to the exterior of the mound. A cluster of chalcopyrite-anhydrite-rich black smoker chimneys emitting fluids up to 363°C is located northwest of the center of the mound. This chimney cluster sits on the top of a 10-20-m-high, 40-50-m diameter cone, the surface of which is covered by a 3-6-cm-thick plate-like layer of massive chalcopyrite and marcasite, with interspersed blocks of corroded massive anhydrite with variable amounts of chalcopyrite and pyrite. The remainder of the top of the mound (at a depth of 3660-3665 m) is relatively flat with an irregular surface. Samples of amorphous Fe-oxyhydroxide and silica have been recovered from the west, south, and east rims of the mound, and bulbous mixed Zn, Fe, and Cu-Fe sulfides with cavities filled by amorphous silica were recovered from the northern rim and central portions of the mound. A complex of white smokers venting fluids from 260° to 300°C is located in the southeast quadrant of the mound approximately 70 m away from the black smoker complex; these "Kremlin"-like spires are small (1-2 m) and are

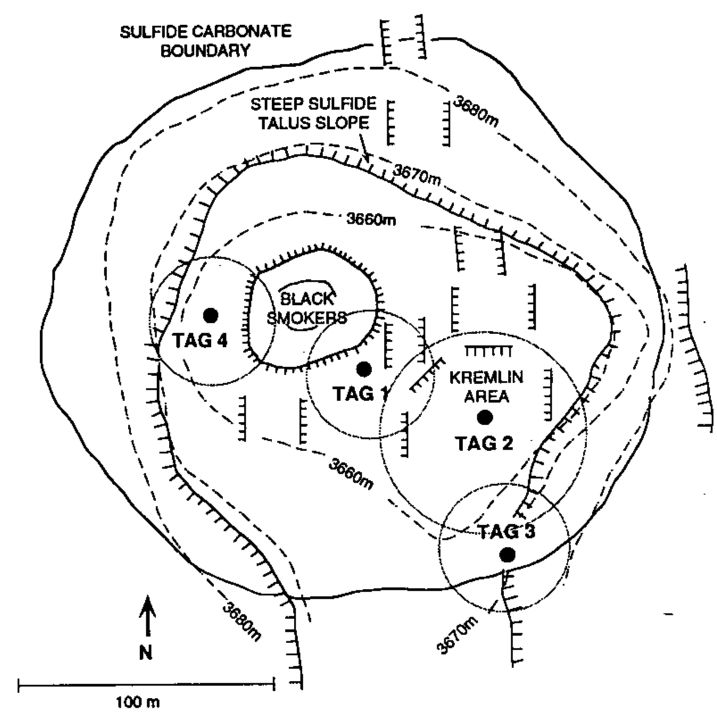

Figure 2. Plan view of the active TAG hydrothermal mound showing the Leg 158 drill holes in relation to the principal boundaries and tectonic features as derived from submersible observations and photography. The circles around each hole location denote the bounds of the areas that might be affected during drilling operations.

composed dominantly of low-Fe sphalerite with minor amounts of chalcopyrite, pyrite, and amorphous silica. Fluids from the white smokers have a very low pH, contain no magnesium, and contain lesser amounts of iron than the black smoker fluids. They are thought to be derived from the black smoker fluids by conductive cooling plus small amounts of mixing with seawater and precipitation of sulfides within the mound.

The distribution of sample types, their mineralogy, and the distinct compositions exhibited at the black smoker and Kremlin locations, suggest a flow pattern within the mound similar to that shown in Figure 1. Fluid exiting the black smoker complex is extremely focused. Fluid emanating from the Kremlin area has undergone conductive cooling and mixing with seawater as evidenced both by the presence of amorphous silica and the chemistry of the fluids. As the fluid cools and circulates within the mound, pyrite is precipitated, and blocks of this material are exposed during mass-wasting.

Scientific Objectives

The overall scientific objectives of drilling at TAG are to investigate fluid flow, geochemical fluxes and associated alteration and mineralization, microbiological processes, and the subsurface nature of an active hydrothermal system on a slow-spreading, sediment-free mid-ocean ridge.

Within the near-surface part of the hydrothermal system, Leg 158 will investigate:

1. The temporal and spatial variation in the mineralogy, chemistry, and physical properties of the hydrothermal precipitates
2. The spatial and temporal variation in the composition of the circulating fluids and the effects of conductive cooling and mixing on the composition of these fluids and their relationships to mineralogical variations within the deposits
3. The method of fluid circulation within the deposit and the spatial characteristics (focused or diffuse) of the flow
4. The effects of fluid circulation within the mound, e.g., possible remobilization and concentration of metals in distinct zones
5. The physical and chemical effects of epigene and supergene alteration reactions on the deposits, and on the fluxes of elements between the deposits and seawater

In the stockwork zone below the surface deposits, studies aim to clarify:

1. The variation in mineralogical and chemical composition of deposits in this zone
2. The degree to which fluids have reacted with the adjacent host rocks, the nature of the rock-seawater interactions, and subsequent effects upon the magnetics
3. The physical and hydrogeological properties of the upper crust in this zone
4. The chemical composition of the hydrothermal fluid in this zone
5. The mechanism focusing the fluid flow within this part of the hydrothermal cell
6. The amount of heat exchanged in the system and the associated energy fluxes

Drilling Strategy

Leg 158 will complete a transect of three (possibly four) holes across the TAG mound (Figure 2). The first proposed hole will be TAG-2, which will be a reentry hole that will be drilled to at least 500 m on this leg. TAG-2 is located off-center in the "Kremlin" area, where warm (250°C) waters are discharging from small (1-2 m) high chimneys composed dominantly of Zn-Fe sulfides. Heat flow is quite high, on the order of 3-9 W/m^2. The surface of the mound at this location is relatively flat, less than 5 m of relief over an area of roughly 50 x 50 m, and is suitable for setting a guide base. It is also located over the magnetic low and thus has a high probability of intersecting the stockwork zone. Fluids emanating from this region are believed to have undergone conductive cooling and mixing with seawater within the mound; consequently, this hole will provide information on the mineralogical and chemical variability within the mound related to these different fluids and physical controls. If drilling conditions are favorable, then the highest priority will be to continue drilling this hole.

Proposed secondary holes TAG-1 and TAG-3 will be shallow (at least 200 m), non-reentry holes and will be designed to penetrate through the hydrothermal deposits and into the top of the altered basaltic crust. The decision as to whether these holes will be drilled will depend on the results of drilling TAG-2. Proposed hole TAG-1 is located near the center of the mound on the shoulder of the central cone in an area that has a slope of less than 10° and is roughly 20-30 m wide. This is the area closest to the black smokers that, from submersible observations, is the most suitable for drilling near the region of high-temperature activity. Heat-flow values are extremely variable within 20 m of the black smokers. This hole is designed to penetrate through the entire section of hydrothermal deposits and into the uppermost portion of the highly altered crust. In this region, large black smoker chimneys occur, from which hot (363°C) fluids are emanating. The chemistry of the fluids suggests that they have not mixed with seawater in the subsurface region of the mound, and it is likely that the ascending flow is well-focused beneath the chimneys (Figure 1). This hole provides the best opportunity to recover a stratigraphic section of the hydrothermal mound and to determine the nature of the fluid flow beneath the most active part of the mound.

Proposed hole TAG-3 is located at the south-southeastern edge of the mound, out of which cool (<100°C) waters are diffusing. In this area, heat flow is very high (5-10 W/m^2) on the sedimented terraces that form the slope down from the Kremlin area to the volcanic center south-southeast of the mound. Drilling this hole will have two objectives: first, investigation of the degree of sulfide oxidation, and the mobilization and reconcentration of trace elements; second, determination of differences in the plumbing system within the mound related to diffuse, rather than focused, flow.

There is a coherent belt of very low heat flow (<20 mW/m^2), 20-30 m west of the black smokers, on the sulfide rubble plateau that surrounds the central smoker peak. To investigate possible recharge within the mound, this area is suggested for proposed hole TAG-4. Time may not permit drilling this hole, as it is the fourth priority.

LITHOSPHERE PANEL WHITE PAPER

Thematic Panel White Papers

PART I. Introduction and Overview

The Lithosphere Panel (LITHP) of the Ocean Drilling Program (ODP) is responsible for evaluating drilling proposals that address problems concerning the construction, evolution, and destruction of oceanic lithosphere created at mid-ocean ridges, intraplate volcanic centers, and convergent margins. The study of the lithosphere is important in that oceanic lithosphere floors nearly 70% of the globe and lithospheric processes within it provide parts of global heat and geochemical budgets. Interactions between the lithosphere, the biosphere and the hydrosphere affect climate and ocean chemistry. Modern processes of magmatism and hydrothermalism at mid-ocean ridges and convergent margins and deformation and mass transfer at convergent margins provide the only analogs available to us for the interpretation of ancient ore deposits and orogenic belts.

ODP, and its predecessor the Deep Sea Drilling Project (DSDP), have provided information about the age, stratigraphy, structure, and evolution of the ocean basins that could not have been discerned any other way and that have had a profound impact on the earth sciences. The list of problems and hypotheses that could be examined by a drillship is long and formidable and the resources of the scientific community are not such that all of them can be addressed. The priority of some lithosphere objectives has changed and new problems have come to light in the last few years (the impact of large igneous provinces, the recognition of the lateral heterogeneity of oceanic crust, and the complexity of forearc terrains are examples). In addition, technological advances now allow us to undertake projects previously considered untenable. The goal of this document is to review the important accomplishments of ODP in lithospheric drilling, to examine some important unsolved problems, and to recommend the highest-priority objectives for lithosphere drilling in the next ten years of a scientific ocean drilling program.

LITHP White Paper Table of Contents

A. Scientific Objectives as Defined by COSOD I and II

LITHP, as defined in the *Guide to the Ocean Drilling Program* (1988) is concerned with the origin and evolution of oceanic crust and mantle (Figure 1). Specific areas of interest are:

a. Processes of submarine volcanology, intrusion and plutonism; crustal construction at spreading axes; petrology, geochemistry, mineralogy, and magnetic and other physical properties of igneous and metamorphic rocks from the ocean floor, from seamounts, from oceanic plateaus, from volcanic arcs and from basins adjacent to volcanic arcs

b. Processes of submarine hydrothermal circulation; petrology, geochemistry and mineralogy of hydrothermally-altered rocks and hydrothermal deposits from the ocean floor; geochemistry and physical properties of hydrothermal solutions; aging of ocean lithosphere

c. Processes of mantle convection and melting and their relationship to basaltic rocks of the ocean basins; mapping of mantle (geochemical) reservoirs and domains; implications of solid-earth geochemical cycles and fluxes of the global plate tectonic cycle; mass balance problems

Within these broad topical guidelines, specific priorities for lithosphere drilling have been set by two Conferences on Scientific Ocean Drilling (COSOD). COSOD I (1981) identified two high-priority problems: (1) the processes of magma generation and crustal construction operating at mid-ocean ridges, and (2) the processes of hydrothermal circulation in the oceanic crust. This report also recognized other important topics, in particular, the compositional heterogeneity of the mantle and mantle evolution, the aging and evolution of the oceanic crust, the formation of unusually thick crust, the role of transform faults, processes operating in young ocean basins, and island arcs and backarc basins.

COSOD II (1987) examined drilling priorities in the context of global systems, rather than in terms of specific tectonic settings. Lithosphere problems were addressed in workshops on "Mantle/Crust Interactions," "Fluid Circulation in the Crust and the Global Budget," and "Stress and Deformation of the Lithosphere. " The following priorities were identified:

1. To understand the present systematics of the crust/mantle system and the record of its evolution through time, through drilling complete sections of ocean crust. Due to technological limitations, a phased approach of drilling two or three 2-3 km holes into basement, with one of these eventually extended to the Moho was recommended. These long ocean crust sections would be complemented by drilling to examine ridge-crest proceesses, fluxes at convergent margins, seamounts, and oceanic plateaus.
2. To understand fluid flow in three hydrodynamic regimes: active (convergent) margins, active mid-ocean ridges (including bare rock and sedimented ridges), and mid-ocean ridge flanks. Each program should include one or two deep holes (3-4 km) and arrays of 4 to 6 shallow (0.7-1 km) holes.
3. To determine the state of stress stress and deformation in the lithosphere and the physical state of the lithosphere, rifted and passive margins, mid-ocean ridges, and convergent margins.

The scientific problems outlined at COSOD I and II were prioritized and consolidated in the last *White Paper of the Lithosphere Panel*, the *Long Range Plan of the Lithosphere Panel*, and the *Long Range Plan of the Ocean Drilling Program* (Table 1). Many of the objectives outlined by the two COSOD groups have been met in part. Others have not been addressed or have proved to be difficult to accomplish with the available technology

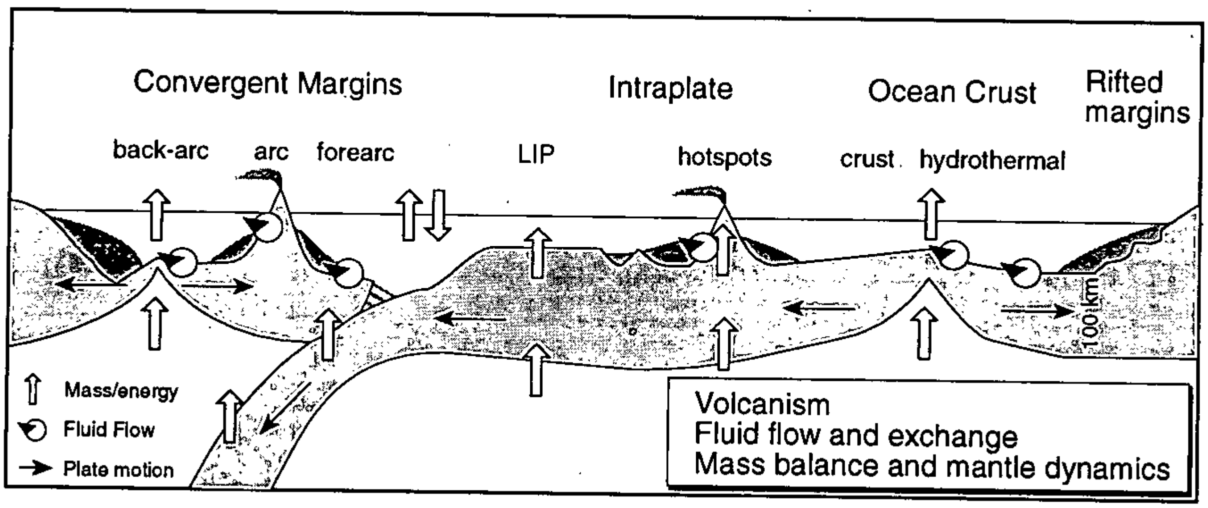

Figure 1. Areas and problems of interest to the Lithosphere Panel of the Ocean Drilling Program

Table 1. Lithospheric thematic problems: objectives of ODP, 1981 to 1990 (no priority to order, except as noted)

COSOD I November, 1981	COSOD II July, 1987	LITHP White Paper May, 1987	LITHP Long Range Plan October, 1988	ODP Long Range Plan 1989-2002 May, 1990
*magma generation and crustal construction at ridges, including natural laboratories	architecture of ocean crust: complete crustal sections; 2-3 km holes, one to Moho	*architecture of the crust: deep hole to Layer 3, offset section drilling (>2)	*structure, composition and alteration history of oceanic crust	explore the structure and composition of the lower oceanic crust and upper mantle
aging and evolution of the oceanic lithosphere	active spreading center processes	*oceanic ridge processes (7-8) crustal accretion processes hydrothermal processes near-axis seamounts natural laboratories	*characterization of processes of magma generation, crustal construction, hydrothermal circulation involved in formation of oceanic crust	magmatic processes associated with crustal accretion
compositional heterogeneity of the mantle	mantle heterogeneity; along and across strike transects of ridges	evolution of oceanic crust (3): structure of old crust seismic aging fluid flow logging of old holes	physical state and evolution of the oceanic lithosphere	dynamics of oceanic crust and upper mantle (OSN, mapping of mantle-derived lavas)
role of transform faults	state of stress and deformation in the lithosphere	fracture zone structure (1-2) and evolution	mantle chemistry and dynamics	plate kinematics and reconstructions
*hydrothermal circulation in the crust	bare-rock hydrothermal systems	oceanic plateaus--age and structure (2)	intraplate volcanism	hydrothermal processes associated with crustal accretion
formation of overly thick crust	sedimented ridge hydrothermal systems	intraplate volcanism (>2) early hotspot volcanoes basement age and trends	rifting and initiation of ocean basins	intraplate volcanism
young ocean basin processes	mid-ocean ridge flank fluid flow	origin of flexural moats (1)	geochemical fluxes and magmatic processes at convergent margins	intraplate deformation
island arcs and back-arcs	composition and structure of seamounts and plateaus	ocean rift initiation (1-2) passive margin sequences young ocean rifts		deformation processes at divergent (passive) margins
	volcanic and non-volcanic passive margins	convergent margins (3-6) offshore reference holes forearc-backarc-arc transects		magmatism and geochemical fluxes at convergent margins
	convergent margin fluxes			deformation processes at convergent margins
	fluid flow at convergent margins			fluid processes at plate margins
	flow patterns in forearcs			

[Note: *highest priority objectives; (2)-number of legs for problem]

Table 1. Lithospheric thematic problems: objectives of ODP, 1981 to 1990 (no priority to order, except as noted)

B. Status of Scientific Objectives at the End of Phase I of ODP (1992)

Progress in achieving the scientific objectives of ODP has been both stunningly successful and frustratingly slow. We have made major advances in our understanding of convergent margin evolution, the composition of the lower oceanic crust, the origin of sediment-hosted ore deposits, and the evolution and alteration of the upper oceanic crust with time. We still, however, have much to accomplish to realize our goals of understanding near-ridge-crest processes and completing a sampling of the entire stratigraphy of the oceanic crust.

The two highest-priority objectives of LITHP have been to understand the architecture (the structure, composition and alteration history) of the oceanic crust and to characterize the near-ridge processes of magmatism and fluid flow involved in the construction of mid-ocean ridge crust. Drilling to address both of these problems demanded substantial technological innovation because of the eventual need for deep drilling and the requirement of recovering fractured, young basalts at ridge crests. We have made tremendous advances in our ability to work and drill in bare-rock and ridge-crest environments. In fact, the ability to work on bare hard rock opened a second avenue for sampling the lower crust—that of offset-section drilling. However, progress towards the scientific objectives of near-ridge-crest drilling on sediment-free ridges has been limited.

Most of the other objectives of LITHP have, however, been addressed at least in part (Appendix 2). This success derives from the breadth of lithospheric problems, which overlap with many problems in tectonics, fluid flow, and even ocean history. Many of these problems can be tackled with conventional rotary-drill methods. As a result, there have been important contributions to our understanding of crustal evolution, intraplate volcanism, convergent margin volcanism in the first phase of ocean drilling, and crustal formation and evolution at sediment-covered ridge crests.

B.1 Architecture and Evolution of Oceanic Lithosphere

A direct knowledge of the structure and composition of the oceanic crust are essential for testing the ophiolite model for oceanic lithosphere, for identifying the origin of seismic boundaries in the crust, and for quantitatively balancing fluid and chemical fluxes between the lithosphere and the hydrosphere. There are two strategies for obtaining samples of the entire oceanic crust: drilling single deep holes through the Moho and drilling exposed, partial sections of the lower crust and mantle (offset-section drilling). Both strategies have yielded some important results.

Offsetsection drilling has yielded the first continuous sections of lower crustal and mantle lithologies. The 500 m of gabbro recovered at Hole 735B (Leg 118) on the Southwest Indian Ridge is the first stratigraphic section of in situ lower crustal material recovered from the oceanic basement. These rocks have provided important new insights about magma chamber processes, magnetization of lower crust, and hydrothermal circulation in the lower crust. The ubiquitous association of shear zones with fractionated gabbros at Site 735B has also demonstrated the intimate link between magmatic and tectonic processes. Drilling during Leg 147 in Hess Deep in the eastern Pacific recovered gabbros and gabbronorites from faster spreading crust, and more importantly, recovered a sequence of interleaved gabbroic and tectonized harzburgites. Harzburgites drilled during Leg 109 on the Mid-Atlantic Ridge provide comparative materials from a slow-spreading environment. Substantial gabbroic and ultramafic sections are expected from drilling in the MARK area on Leg 153. This work should provide us with the first fragments of lower crustal rocks with which we can begin to construct a complete section of the crust.

The offset-drilling results complement the relatively deep drilling now accomplished at Site 504B on the Costa Rica Rift. Site 504B is now over 2 km deep and the hole has penetrated most of the sheeted dike complex and may be into the top of seismic Layer 3. Hole 504B has provided a reference section for the alteration of oceanic crust and a clear yardstick with which to measure models of seafloor generation derived from ophiolite studies and to define fossil oceanic crust formed on the early Earth. Logging and physical properties studies have provided important information on the aging of the crust, and have established the low permeability of most of the section below 200m. Complementary logging studies in Sites 418A and 395A in the Atlantic, and at Sites 801C and 765C on Jurassic crust in the Pacific and Indian Oceans, have provided comparative sections of the physical properties of variously aged, altered crust.

Drilling at Middle Valley (Leg 139) revealed a striking contrast in crustal architecture between sedimented and unsedimented ridges. At the latter, basalt sills and sediments are intercalated in thick sequences. A similar crustal structure was found in drilling on Legs 126, 127, and 129, suggesting that "sedimented-rift architecture" may actually be typical of early rfting stages at many passive margins.

These results have provided some constraints on the lithologies present in different parts of the crust and have allowed an examination of alteration and deformation as the crust ages. The most important remaining goal is to complete the initial offset-section strategy of representative long sections through the major crustal layers and their transitions at both fast- and slow-spreading ridges.

B.2 Magmatic Processes at at Mid-Ocean Ridges

Objectives for understanding magmatic processes at ridges include constraining the composition and stratigraphy of zero-age crust, determining fluid/rock interactions above a magma chamber, characterizing the temporal variability of lavas, providing calibration for geophysical observations, and examining the links between magmatic and tectonic processes. All require drilling in young, fractured basaltic rocks. The technological difficulties of such drilling have proved formidable and the application of narrow kerf diamond drilling to deep ocean work has progressed more slowly than expected. There has, however, been tremendous progress made in what was undiscovered engineering territory only a few years ago. Hard rock guide bases provide support for the drill string which allows spudding into bare rock, a capability important for offset drilling as well as for ridge-crest work. The positive displacement core motors have provided great flexibility in drilling unsupported pilot holes in bare-rock terrains, allowing much more careful site selection.

The high-priority goal of systematic drilling of zero-age oceanic crust and associated hydrothermal systems has not been fully met, in part because the Diamond Coring System (DCS) that is required to complete these investigations is still in the developmental and testing phase. However, Leg 139 drilling in the Middle Valley, the sediment-covered portion of the northern Juan de Fuca Ridge, was a substantial contribution to this effort. The uppermost section of zero age oceanic crust was drilled and determined to consist of interlayered metasediments and basaltic sills in contrast to the extrusive basalt that forms the upper oceanic crust at sediment-free spreading centers. Although sediment-covered spreading centers are not common in today's ocean, sediment-free ridge systems initiated by continental rifting may evolve through an initial stage of sediment-covered spreading. A second achievement of the leg was the deployment of the first CORK—an instrumented borehole seal which can be revisited by submersible to read temperature and fluid pressure and to extract fluid samples. This deployment is the first important, practical step towards establishing seafloor ridge laboratories, which has been a high-priority objective of LITHP and of the InterRidge initiative.

It is clear that the study of ridge magmatic processes is the objective towards which we have made the least progress. An evaluation of the approach to the problem in the next ten years requires a pragmatic look at the viability of diamond drilling and the needs of seafloor laboratories. Alternate strategies employing rotary coring technology may prove adequate to the task in some environments.

B.3 Hydrothermal Processes at Mid-Ocean Ridges

Some of the most exciting results of the first phase of ODP have come from work at hydrothermal systems at sedimented ridges. Leg 139 in Middle Valley, the sediment-covered portion of the northern Juan de Fuca Ridge, succeeded in drilling directly into an active hydrothermal system and was able to safely core and log in rock at temperatures approaching 300°C. The composition of the active hydrothermal field was demonstrated to be related to convective circulation of seawater and is controlled by sub-seafloor metamorphism of the underlying sedimentary and basaltic rocks. A major discovery of Leg 139 was the penetration of 95 m of massive sulfide formed in a slightly older hydrothermal system. The chemical composition of this deposit indicates that it formed from hydrothermal fluids that interacted primarily with basaltic rock at significantly higher temperatures than the active hydrothermal system drilled 5 km to the northwest. Further progress in understanding hydrothermal activity associated with zero age oceanic crust is anticipated from drilling in the TAG hydrothermal field on the Mid-Atlantic Ridge which is scheduled for 1994.

Our understanding of the hydrothermal alteration of the crust has also been furthered by coring and logging of older crustal sections and lower crustal samples at Site 504B, Site 735B, Site 894G, and Site 801C. There has also been some success in looking at ridge flank fluid circulation on Legs 111 and 148, near Hole 504B.

Drilling at Middle Valley and TAG will accomplish the first part of our goals at hydrothermal systems. Both, however, were designed as two-leg programs, and will likely require additional drilling to completely constrain the hydrothermal flow. Part of the proposed hydrothermal program has been to drill a 1000+ m hole to examine fluid flow in the reactions zone and to provide a permanent instrumentation site. It should be noted that there has yet to be an effort made to examine the felsic volcanic-hosted hydrothermal systems that are important sources worldwide of Cu, Zn, Pb, Ag, and Au.

B.4 Fracture Zone and Transform Tectonics

Drilling within a fracture zone has been attempted only on Leg 118 at the Atlantis II fracture zone in the Indian Ocean and it proved to be a difficult problem. However, drilling on the transverse ridges adjoining some fracture zones has provided valuable scientific returns. Site 735B was drilled on such a platform, and the site was successful partly because of the nature of the smooth wave-cut terrace along the top of the transverse ridge. Drilling planned on Leg 157 on the Vema Fracture Zone's transverse ridge will not only provide a test of the DCS but also will recover a sedimentary section that could constrain the history of vertical motion on the ridge, and hence help solve one of the nagging problems in fracture zone tectonics.

B.5 Lithospheric Stress and Mantle Dynamics

Most sites that return enough basement provide important data points for building models of mantle compositions and consequently of mantle evolution and dynamics. Good measurements of stress directions in the lithosphere require holes at least 500 m into basement as well as adequate borehole televiewer records of the hole to identify the shape and orientation of breakouts. Such stress measurements have been made at only a few oceanic sites, including the Mariana-Bonin forearc (Legs 125/126), the Japan Sea (Legs 127/128), and Site 504B. The problem with acquiring a greater number of measurements is that many sites do not penetrate deeply enough into basement to provide viable stress indicators.

Both lithospheric stress and mantle dynamics are objectives that can be addressed in part by coordination with other programs and objectives. Major boundaries within the mantle have been identified, such as that along the Antarctic Discordance, at which drilling could constrain the age and motion of that boundary within the mantle.

B.6 Large Igneous Provinces

Large igneous provinces (LIPs) are regions where rapid or episodic volcanism has produced unusually large accumulations of rocks. Such areas include oceanic plateaus, hotspots and linear seamount chains, and volcanic flows and intrusions associated with continental rifting, and ocean basin flood basalts. The importance of these areas to the thermal and geological evolution of the Earth has only recently been recognized, and they are now a high-priority objective for scientific ocean drilling. ODP Legs 104, 113, 114, 115, 119, 120, 121, 129, 130, 143, and 144, although primarily reconnaissance drilling, have all examined some aspects of LIPs and have paved the way for implementation of lithosphere drillng strategy for LIPs.

Drilling on the largest oceanic plateaus Kerguelen (Legs 119/120) and Ontong-Java Plateau (Leg 130) has confirmed the basaltic character of uppermost igneous basement, has suggested that they formed on time scales of 1 my, and has provided some geochemical information on LIP basalts. A drilling program focused on testing models for the eruption and evolution of one of these plateaus is now possible and should be a high-priority.

Scientific drilling has produced important results from hotspot and intraplate volcanoes. In the Indian Ocean, Legs 115 and 119 further substantiated the hotspot origin of the Mascarene Plateau and Chagos-Laccadive Ridge, as did Leg 121 for the Ninety-East Ridges. Paleolatitude determinations from these legs have revived the concept of "true polar wander" and has renewed debate about the interaction between hot spots, the lithosphere, and convection in the mantle. Legs 143 and 144 on Pacific atolls and guyots expanded our data base of lava compositions derived from the Pacific mantle and suggest complex lithospheric uplift and subsidence histories. Additional basalt samples from Southern Ocean sites on the Maud, Meteor, and Islas Orcados Rises (Legs 113 and 114) have provided information on mantle compositions. Ocean basin flood-basalt samples from the Nauru, East Mariana, and Pigafetta Basins (Leg 129) have demonstrated their contemporaneity with and compositional similarity to neighboring Ontong-Java basalts, suggesting that they are components of the same LIP.

A major focus of the first phase of ocean drilling has been the development of rifted passive margins. The basaltic nature of the seaward-dipping reflectors along continental margins was established on Leg 104 across the Vøring Plateau. Beneath the seaward-dipping wedge, dacites and andesites were sampled. Leg 104 samples also provide a record of subsidence and sedimentation that constrain the history of rifting. These volcanic rifted margin results complement drilling on the Galician (Leg 103) and Iberian (Leg 149) margins, where peridotites and other mantle rocks were uplifted to above sea level by extension and faulting, in the absence of voluminous volcanism. More detailed pictures of both volcanic and non-volcanic rifted margins should emerge from analysis of results from drilling along the Iberian margin on Leg 149 and drilling across the East Greenland margin on Leg 152. These two legs are parts of multi-leg programs employing a conjugate margin, transect strategy to better understand volcanic and non-volcanic margins. Other drilling in rifted margins in the Tyrrhenian Sea (Leg 107) and the Exmouth Plateau in the Indian Ocean (Legs 122/123) provide a set of holes that will, upon completion of the North Atlantic Rifted Margin legs, allow development of continental rifting models in detail that was not previously possible.

B.7 Convergent Margins

Convergent margin drilling has been one of the most active and diverse projects of ODP in its first phase. Drilling has occurred in accretionary and non-accretionary margins, forearcs, backarcs, and arcs. All of this drilling, in one way or another, contributes to the objective of understanding geochemical fluxes and tectonic processes at convergent margins.

Leg 110 in the Barbados accretionary complexes and Leg 131 in the Nankai Trough both penetrated through the decollement above the subducting slab and constrained patterns of fluid flow within sedimented prisms and provided the first data needed for mass balancing inputs to subduction zones. Drilling in the Cascadia Margin on Leg 146 successfully drilled parts of the prism with both diffuse and focused flow and also deployed borehole seals in the prism.

Constraints on fluid flow in the forearc also came from Leg 125, on the non-accretionary Mariana forearc. Drilling established that structural highs on the trench-slope break were indeed diapiric serpentinite flows, and that fluids venting from those serpentinites were derived in part from dehydration reactions in the downgoing slab. These results provide the first direct evidence of dewatering of the slab past the toe of the accretionary prism and also provide an analog for serpentine terrains such as those in parts of the Franciscan formation. Clasts in the serpentinites from Leg 125 also yielded the first blueschists from an active subduction zone, providing the first direct confirmation for models of blueschist formation by active subduction. Site 786B on the Izu-Bonin forearc also provided a record of hydrothermal mineralization in dikes intruded into forearc basin sediments.

Legs 125 and 126 in the Mariana and Bonin forearcs provided a new picture of the dynamics of forearc evolution. The initial construction of the arc in the Eocene was by widespread (>300 km wide) volcanism with voluminous boninite and depleted arc tholeiite eruptives; this volcanism occurred in an extensional setting and may have proceeded by seafloor spreading. A similar scenario was inferred from drilling in the Tonga forearc on Leg 135. If this result is generally applicable, it provides the most striking parallel yet found for the origin of so-called "supra-subduction zone" ophiolites. Legs 125, 126, and 135 also documented the occurrence of tectonism and volcanism in the forearc, well after substantial arcs existed and the forearcs were supposed to be cold. Leg 126 also settled a long-standing debate by demonstrating that arc activity was confined to central edifices, with almost no interarc eruptions; the leg also demonstrated that drilling coarse volcaniclastics with reasonable recovery was indeed possible.

Backarc basin drilling in the Sumisu Rift (Leg 126), the Japan Sea (Legs 126/127) and the Lau Basin (Leg 135) has provided data to construct quantitative models of backarc development. Sumisu Rift and Lau Basin results show that depleted MORB-type mantle is available in the backarc at the very earliest stages of rifting, and then becomes variously contaminated with an arc component, eventually moving back towards purer MORB compositions. Both the Japan Sea and Lau Basin legs documented the initial rifting of the basins by stretching of arc or continental crust, succeeded by true sea-floor spreading. Both basins appear to have nucleated along strike-slip boundaries and opened by rift propagation into the preexisting arc. A significant result from drilling in the Sumisu Rift was the recovery of basaltic pumice or mousse in water depths over 2000 m, challenging the long-held assumption that violent, gas driven eruptions could not occur in deep water.

The drilling to date in convergent margins has raised some important testable hypotheses, but has also left a number of problems unaddressed. There has still not been a coordinated experiment to try to mass balance the material transfer across subduction zones. The margins where there are simple and well-documented records of volcanism are not those where we have good records of the offshore crustal section. Our constraints on the volume of eruptive products in different settings in any arc are still very poor.

One of the surprising gaps in convergent margin drilling is that there has yet to be a leg directly addressing the controversy surrounding the origin of "supra-subduction zone" ophiolites, despite the fact that many more ophiolites are now interpreted to have in a setting other than a "normal" mid-ocean ridge. Nor has there been identified a good place to study analogs for the silicic-volcanic hosted ore deposits that host many of the base metal deposits in the ancient geologic record.

C. Summary of Recommendations for Lithospheric Drilling for Phase II of ODP (1993-1998) and Beyond (1998-2003)

The achievements of ODP in meeting objectives of LITHP have been substantial, but there are many objectives that have not been met at all, and others that are new or have only been partly completed. Some of the outstanding scientific problems involved in the origin and evolution of the oceanic lithosphere are discussed below. The scientific problems discussed in Part II are all important and their solution could occupy the program full-time for a number of years. However, because of the limited time available in the next ten years for drilling lithosphere objectives, LITHP views some of these scientific objectives as first-order problems whose solutions should be a priority of the lithosphere component of ocean drilling. These first-order problems include (in no order of priority):

Oceanic Lithosphere

- Crustal evolution—drilling along a flow line
- Hydrothermal processes coordinated with experiments mand monitoring efforts
- Lithosphere structure and composition—offset drilling and deep drilling
- Initiation of rifting—drilling in an area of young or incipient rifting
- Mapping of mantle domains

Large Igneous Provinces (LIPS) and Intraplate volcanism

- Mantle plumes and continental breakup
- Composition and timing of the formation of large oceanic plateaus
- Evolution of intraplate volcanoes

Convergent Margins

- Arc initiation and supra-subduction zone ophiolites
- Backarc initiation and source distribution
- Subduction zone mass balances and geochemical fluxes
- Hydrothermal fluxes and deposits in convergent margin settings

Some of these objectives overlap those of other panels, and could be addressed in multi-objective legs; others will require dedicated legs of drilling. These objectives need to be met in a two-phase program: first, legs that occur between now and 1998 and those that occur between 1998 and 2003. The first phase is partly set, through 1995, and the final three years of this work will be, realistically, with current technology on the present platform. The objectives for the second phase, as outlined here, may be accomplished with the present platform, but require the completion of the technologic advances begun in the first phase of ocean drilling including a system, like DCS, capable of recovering fractured, young basalts and samplers that can recover in situ fluid samples.

C.1 Phase 1 Recommendations: 1993-1998

Objectives to be completed by 1998 (not in any order of priority; several of these will be accomplished in part by drilling already scheduled through 1995):

- Obtain significant lengths of lower crustal and upper mantle rocks at slow- and fast-spreading ridges and, ideally, at least one long section through the transition between the two using an offset-drilling strategy. The aim of this work is to identify the first-order variations in the composition of the lower crust and mantle and to provide data to determine the best location for a deep hole or a detailed offset-section experiment during Phase 2 (in part addressed by Hess Deep, 504B, MARK, and the return to 735B).
- Complete one experiment to examine the evolution of mantle plumes, which could include either the evolution of a large intraplate volcanic system (in part addressed by drilling in the Canary Islands in the scheduled VICAP project).
- Complete the first phase of drilling on rifted margins to examine the association of continental rifting and break-up with large volcanic provinces (in part addressed by Legs 149 and 152 as part of the North Atlantic Rifted Margins project); a related part of this experiment could be drilling in a young rift basin.
- Complete second phase of drilling in a sedimented ridge and a bare-rock hydrothermal system. This drilling will likely be with conventional technology and provide an array of shallow holes at each site, some of which will be instrumented and suitable for long-term experiments. Results from this work will be used to assess the prospects and importance for a deep (1000+ m) site in one of the hydrothermal systems during Phase 2 of the project).
- Conduct at least one drilling experiment to test models for the timing, cause, and eruption of large igneous provinces, most likely at one of the two giant oceanic plateaus, Ontong Java or Kerguelen. This drilling will employ existing technology to drill an array of shallow (<200 m) basement holes and at least one deep (~500 m) basement hole in a LIP.
- Complete one convergent margin transect (this may mean simply adding holes to an existing array) designed specifically to test models of mass balance in subduction zone and sediment subduction suggested by recent geochemical work.
- Make a specific test of the supra-subduction zone ophiolite hypothesis either by testing models for the structure and composition of forearc terranes or of backarc basins. Such a leg would address other convergent margin objectives as well.
- Drill one experiment designed to test models for the aging and alteration of the oceanic lithosphere and to constrain models for the evolution of the seismic structure of oceanic crust with time.

As many of the above-listed drilling objectives as possible should include holes to sufficient depth to allow estimates of the state of stress in the lithosphere.

- Make an organized effort to assess the importance of and commitment to the following:
  - i. The advantages of borehole seismometers for the Ocean Seismic Network. If these are deemed to be essential (as opposed to well-coupled OBS arrays) begin emplacement by 1998. This review should include an assessment of other geophysical observatories that could be included in these downhole laboratories (i.e., 3-component magnetometers).
  - ii. Determine the need and technical requirements for natural laboratories—i.e., what instruments need to be in holes, how deep do the holes need to be, and how close to the ridge crest must those holes be. This evaluation should proceed in consultation with InterRidge.
  - iii. Make a firm evaluation of the DCS, regarding both its technical capabilities and its financial support. This will require at least two sea tests before 1998.
  - iv. Evaluate the technical and fiscal requirements for deep drilling—i.e., 4-6 km below seafloor in 4000 m of water—and the feasibility of incorporating this type of drilling within ODP.

This list of objectives should serve as a guide to prioritizing lithosphere drilling in different parts of the ocean. LITHP recognizes that not all of the objectives will be accomplished by 1998 (there is about 1.5 times more drilling listed than is available), However, LITHP believes that we can make significant progress on several of these problems by 1998, assuming a strategy of about 1.5 legs a year drilling arrays of shallow to intermediate depth holes (<1000 m) as we having been doing to date. Some of these objectives will also be addressed on legs of interest to other panels.

C.2 Phase 2: Objectives for 1998-2003

The specific drilling priorities for 1998-2003 will depend, of course, on the results achieved in the next few years. However, it is clear that, given our priorities through 1998, there will be a number of critical lithosphere problems yet to be solved. Our suggested goals for the next five years of drilling are:

- To examine the characteristics of the reaction zones beneath large hydrothermal deposits
- To continue the offset-section characterization of the lower crust, focusing on sampling long sections through the transition zones between principal components of the ocean crust
- To constrain the crustal structure of large igneous provinces and to examine eruptive mechanisms and timing
- To sample the upper crust at or near a ridge axis to examine the processes of crustal construction and modification and to constrain models of ridge magma chambers
- To complete mass balance experiments at a convergent margin by sampling the deeper portions of a forearc to constrain fluid and mass partitioning
- To examine the link between mantle plumes and the development of continental margins by examining a volcanic continental margin away from a plume
- To study the genesis of ore deposits in environments other than mid-ocean ridges that might be analogs for the large terrestrial deposits
- To evaluate the dynamics of mantle reservoirs by defining geochemical domains and by augmenting the global seismic network

Most of these objectives are likely to be answered by drilling fewer, but significantly deeper holes than we have been doing to date (approximately 1-2 km deep, in about 4 km of water). Each such site will probably require two legs of effort, and we recognize that only 3 or 4 of these objectives will likely be completely fulfilled by 2003. The prioritization of these objectives will depend on the quality of sites available to accomplish them, the interest of other panels, and the quality of the proposals prepared to address these issues. Although our objectives through 2003 are all within the capabilities of the present drilling platform, achievement of longer-term lithospheric objectives will require drilling holes 4-6 km deep. Furthermore, the sampling of near-ridge upper crust will require the development of a viable DCS or the development of a suitable alternate strategy for recovering fractured, brittle rocks.

The strategy outlined here does not include all of the ten high-priority objectives listed at the beginning of this section; our listed strategy is focused on legs that will be largely devoted to LITHP objectives. As in the past, we expect that many problems of LITHP interest will be part of projects of interest to other panels, and LITHP will continue to champion multi-objective legs.

It should also be said that, in the end, LITHP is interested in good, well-thought out science that promises to make an important contribution to our understanding of the origin and evolution of the lithosphere broadly defined. The discussion here is based on what we see now as science priorities and problems; these are the topics that we plan to actively pursue and foster, given what we know now. As they have in the last ten years, those problems and priorities will change and expand in the next ten years. LITHP will always carefully consider any proposal for drilling that addresses problems of lithospheric evolution. LITHP strongly endorses the view that international ocean drilling is thematically-driven by proposals from the community—the intent of this document is to foster the development of those proposals.

PART II. Scientific Problems and Objectives

A. Oceanic Lithosphere

A.1. Processes at Mid-Ocean Ridges

Much of the Earth's crust is created at oceanic spreading centers. Seismic data have shown that the velocity structure of that oceanic crust is remarkably uniform at a global scale, and is defined by two major velocity intervals: Layers 2 and 3. Studies of ophiolites and comparison with the variety of extrusive and plutonic rocks recovered from ridge-crest environments indicate that Layer 2 may comprise basalt flows grading downward into diabase dikes, and that Layer 3 may be gabbroic. Drilling at Hole 504B on the flank of the Costa Rica Rift provides support for this layered geological model. However, sample studies, geological mapping and geophysics in the axial region of slow-spreading ridges such as the Mid-Atlantic and Southwest Indian Ridges, suggest that structural and lithological heterogeneity may be more typical of the crust in magma-starved ridge environments. The main characteristics of such environments appear to be the lack of a long-lasting axial magma chamber, the existence of complex interactions between magmatic, deformational, and hydrothermal processes (best documented so far in the gabbro section drilled at Hole 735B in the Southwest Indian Ocean), the exposure of upper mantle rocks on the seafloor and their intrusion by gabbro dikes and sills, and the presence of large, offset, ductile and brittle normal faults. It is clear that an understanding of the construction of the oceanic crust can only come from an integrated examination of magmatic, tectonic, and hydrothermal processes at both fast- and slow-spreading ridges.

A1.1 Magmatic and Tectonic Processes

The magmatic system at ocean ridges can be viewed as having three basic components: (1) the production of melt in the upper mantle and its segregation and ascent to crustal depths, (2) the evolution of magmas in reservoirs and their crystallization to form gabbros, and (3) the eruption of basaltic melts on the seafloor, forming the uppermost oceanic crust. Tectonic processes linked with plate divergence at mid-ocean ridges, and with the associated motion along large and small transform faults, are intimately coupled with the magmatic evolution of the crust. Understanding crustal accretion and constraining the interplay between magmatism and tectonism at and near the ridge axis is of primary importance to LITHP. The most important questions that must be answered to better understand this system are:

- What is the horizontal and vertical extent of the zone of melt production in the upper mantle?
- How and why is magma focused at a narrow ridge axis when it is presumed to be generated from wide melt zone in the mantle?
- What are the shapes, sizes and longevity of magma chambers?
- What are the relationships between magma chambers dynamics and solid state deformation of the newly accreted axial lithosphere?
- What are the characteristic length and time scales of ocean ridge magma production?
- What is the role and extent of off-axis volcanism in the formation of oceanic crust?
- How is oceanic crust chemically and physically modified as it is transported away from the ridge crest?
- What can be learned about lithospheric accretion processes through studies of lower crust and upper mantle sections exposed within or near fracture zones?

A1.2 Hydrothermal Processes

Ridge-crest hydrothermal systems are an integral part of the transfer of heat from the Earth's interior to the surface and are an important link between the lithosphere and the hydrosphere. Heat lost through hydrothermal circulation has a pronounced effect on the size and longevity of crustal magma chambers. The circulating fluids are responsible for a major part of the flux of Mg and other elements into or out of the oceans and can result in formation of metallic sulfides that are analogous to economically-important ore deposits on land. Understanding the mechanisms and consequences of ridge-crest hydrothermal activity and the effects on the composition of both seawater and oceanic crust is a basic goal of lithospheric studies.

The deposits formed by submarine hydrothermal systems vary widely in form and composition depending on the temperature and composition of the hydrothermal fluids and the interaction of the hydrothermal system with the seafloor depositional environment. The most spectacular are the high-temperature black smoker and lower-temperature white smoker systems found at sediment-free ridge crests such as the East Pacific Rise (fast-spreading) and Mid-Atlantic Ridge (slow spreading). These systems discharge hydrothermal fluid on the seafloor at up to ~400°C and precipitate iron, copper and zinc sulfides in chimneys and mounds in response to mixing with cold seawater. Chemical potential energy of dissolved constituents in the fluids (mainly H_2S) is converted (via microbial intermediaries) into the biomass of unique biological communities that exist independent of photosynthetic food sources. Hydrothermal systems associated with sediment-buried ridge crests (Middle Valley, northern Juan de Fuca Ridge; Escanaba Through, southern Gorda Ridge; Guaymas Basin, Gulf of California) are modified by the presence of relatively impermeable sediments that blanket the volcanic heat sources. Chemical reactions between the hydrothermal fluids and the sediments (e.g., Escanaba Trough and Guaymas Basin) change the composition of the hydrothermal fluids and result in massive sulfide deposits that differ in composition from those formed with basaltic rock as the only metal source. Thermal maturation of organic matter in the sediments leads to generation of petroleum and might have played a role in the formation of petroleum occurrences in the geologic record. Diffuse venting of low-temperature (10-100°C) fluids results from subsurface mixing of high-temperature hydrothermal fluids with seawater. The seafloor expression of these systems is the formation of metallic oxide and silicate deposits, however metallic sulfides may be deposited beneath the seafloor. Hydrothermal systems at young oceanic ridges may be associated with high-salinity fluids (Red Sea) that can form submarine brine pools that efficiently concentrate hydrothermal precipitates and form large, laterally continuous metalliferous mud deposits.

There are four essential components to any hydrothermal system: (1) a heat source, (2) a source rock, (3) a permeable medium, and (4) a circulating fluid. Processes operating in hydrothermal systems are highly interactive. Thermal energy is provided by hot rock or magma at shallow crustal levels (2-3 km); high-temperature pulses of hydrothermal activity may be related to periodical replenishment of a magma chamber and shallow-level intrusions. Conductive heat transfer from the magma chamber to the host rock intensifies the local state of stress through expansion of the fluid that saturates the host rock, resulting in hydrofracturing and increased permeability, which in turn augments fluid circulation and the rate of heat transfer. This may be balanced by the precipitation of alteration assemblages in veins of the fracture network, decreasing permeability. Despite the fundamental nature of this interface between molten and cracked rocks, it is one of the most poorly understood aspects of any active hydrothermal system.

A basic understanding of submarine hydrothermal systems requires answers to the following questions:

- What is the size, shape, depth, temperature, and time-dependent behavior of the heat source?
- What is the nature of the high-temperature reaction zone?
- What are the spatial and temporal variations in permeability, composition, and alteration of the host rocks?
- What are the time/space variations in physical properties and composition of the circulating fluids?
- What are the feedback loops linking the evolution of these principal components?

A1.3 Fracture Zone and Transform Fault Processes

Though the kinematic role of transform faults has long been understood, transforms and their off-axis extensions remain the most enigmatic of the common features on the seafloor. Fracture zones often include the deepest points on the mid-ocean ridge system, a fact generally attributed to a thin crust caused by excess cooling at the ridge-transform-intersection (RTIs). Paradoxically, some RTIs include a topographic high (especially on fast spreading ridges), which may be caused by enhanced volcanism. Transforms also often include median or transverse ridges that are often shallower than the adjacent spreading ridge segments. These features are poorly understood, and a number of mechanisms have been suggested for their presence. These include excess volcanism (a leaky transform), serpentinization of the upper mantle, flexural deformation related to cooling, and dynamic uplift.

Fracture zones often expose rocks believed to originate in the lower oceanic crust or upper mantle. In fact they provide some of the best support for the "ophiolite" model for oceanic crust because most of the stratigraphic units of ophiolites have been observed in various fracture zones. However, fracture zones are, by definition, anomalous (but common), and therefore caution needs to be exercised when extrapolating fracture zone observations to the crust in general.

There are a number of unanswered questions concerning fracture zone volcanism and tectonics:

- How do fracture zones affect the dynamics of the adjacent spreading ridges?
- What is the mechanism by which median and transverse ridges form?
- What controls the morphology of ridge-transform intersections?
- How is the strike-slip faulting associated with seafloor spreading distributed in time and space in the relatively wide transform fault zone?
- How does the bathymetry of fracture zones evolve with time?
- How do fracture zones behave in their "inactive" or "aseismic" extensions? Do these extensions accommodate hydrothermal activity in older crust? Are they the site of extensive ongoing vertical tectonics?

A.2 Physical State and Evolution of the Oceanic Lithosphere

A knowledge of the thermal and mechanical evolution of the oceanic lithosphere, and the stresses acting on the plates, is important for understanding a number of fundamental problems, including the subsidence history of oceanic crust, the kinematic evolution of plate boundaries, and the coupling between lithospheric and asthenospheric processes. Flexure of the lithosphere due to loading at mid-plate volcanoes or unloading at rifted margins provides opportunities to study the mechanical properties of the lithosphere to hotspot volcanism or rifting events. In both environments, sediment sequences are preserved that record onlap and offlap patterns related to variations in the effective elastic thickness of the plate and uplift/subsidence histories. Dating of sediment sequences within flexural moats of volcanoes or on rifted margins can provide constraints on the evolution of the lithospheric thermal structure and flexural strength.

A variety of observations demonstrate that the physical and chemical characteristics of oceanic crust evolve as the crust ages. Near the ridge axis, hydrothermal convection driven by the axial volcanism produces locally intense alteration of the crustal rocks; the hydrothermal may be especially focused along high-permeability pathways near the seafloor. Extensional faulting occurs as the crust moves out of the neovolcanic zone, modifying the porosity and permeability structure. Seismic studies in the Pacific have shown that the low velocity uppermost crust (Layer 2A) thickens by about a factor of two within the first few hundred thousand years, and then the velocities within Layer 2A gradually increase as the crust ages to 20 (or more) until Layer 2A becomes indistinguishable from the higher velocity Layer 2B. The near axial thickening of Layer 2A may be related to basaltic flows extending (or erupting) off-axis or to an increase in shallow porosities due to faulting and fissuring. The gradual off-axis increase in Layer 2A velocities is generally attributed to the pore-filling alteration products of passive hydrothermal circulation cells; these cells are initially open to sea water, but are eventually isolated from sea water by an impermeable sediment cover.

The integrated effects of seawater-rock interaction result in the vertical metamorphic gradients observed in ophiolite sequences and in Hole 504B in the oceanic crust. The chemical flux between the hydrosphere and the lithosphere is most intense within the uppermost oceanic crust (but may extend to the lower crust as well). The effects of these chemical fluxes extend far beyond the bottom of the ocean, for the altered oceanic crust is eventually subducted thereby influencing the evolution of volcanic arcs and the flux of crustal material into the mantle. In spite of the global importance of the energy and chemical fluxes between the hydrosphere and the lithosphere, the timing, magnitude, and in some cases, even the direction of these fluxes remain poorly known.

The above observations lead to a number of fundamental questions about the evolution of the ocean lithosphere:

- How does the strength and state of stress in the lithosphere change as it ages or is affected by hotspots or rifting?
- What causes the thickening of the low-velocity, high-permeability Layer 2A in very young crust?
- What causes the long-term increase in upper crustal seismic velocities?
- If the long-term increase in seismic velocities is caused by precipitation in pores from hydrothermal circulation, what is the timing and nature of the circulation?
- Is the evolution of the uppermost crust accompanied by circulation in, and alteration of, the rocks of the mid and lower crust (Layers 2B, 2C and 3)?
- Does the crust continue to evolve beyond the 30 million years "limit" indicated by seismic experiments?
- How much geochemical exchange occurs between the crust and the overlying sediments and water?

A.3* Structure and Scale of Compositional Variability in Crust and Upper Mantle

The global oceanic spreading center displays significant variations in its morphology, crustal thickness, gravity and chemical composition along axis. In addition, the ridge displays a pattern of tectonic segmentation that is observed at scales ranging from 10^1 to 10^2 kilometers. Often the observed petrological provinces correspond with the defined structural segmentation. Since MORBs are produced from pressure release melting of the upper mantle, the observed spatial zonation in basalt composition supports the belief that the upper mantle beneath the ridge must be chemically heterogeneous on similar scales. The origin of these mantle heterogeneities and their size and mechanism of dispersion in the upper mantle beneath the ridge are still unknown. However, the existing spatial variations in oceanic crust can provide valuable insight into the processes relating to temporal changes in the volumes of melt formed in the mantle and the patterns of delivery to overlying crust.

The observed variations in ridge structure and composition are a consequence of the temporal and spatial changes in the MORB source regime and the mantle melting conditions. In order to understand ridge magmatism and crustal formation, we need to document the nature and scale of mantle heterogeneities not only at zero age, but also for older oceanic crust. At the present time, our knowledge of the ridge system is both spatially and temporally restricted since the majority of the petrologic and geophysical data have been collected in close proximity to the sparsely sedimented active ridge crest. The geochemical record that is preserved in the oceanic crust away from the ridge axis is concealed beneath sediments and is accessible only by drilling. Systematic off-axis drilling will provide the required spatial and temporal sampling necessary to adequately evaluate the processes responsible for producing spatially-variable oceanic lithosphere.

Long-term questions of mantle composition, heterogeneity and dynamics are of fundamental importance to our understanding of the differentiation of the mantle, plume driving forces, and the evolution of the ocean basins and continents through geologic time. Apart from the information on the chemistry and dynamics of the mantle contained in the chemical and isotopic signatures of lavas erupted along ridge, at seamounts and hot spots, and on oceanic plateaus, a complementary perspective comes from three-dimensional seismic imaging of the mantle. Tomographic images of the mantle show large regional variations in the seismic velocity of the upper and lower mantle that can be related to patterns of mantle convection. Integrating these geophysical observations with a global program of geochemical mapping holds great promise for increasing our understanding of the mantle over the next decade. Important questions to be addressed include:

- Where are the major geochemical boundaries in the mantle?
- How long have those boundaries persisted?
- How far in time and space can present-day variations in axial lava compositions be traced?
- How does the seismic structure and bulk composition of the crust change with time?

A.4 Contributions From Drilling

The answers to almost all of these questions relating to the formation and evolution of the lithosphere will require a multi-disciplinary approach involving detailed geologic mapping and sampling, geophysical experiments, and long-term monitoring of selected sites along the ocean ridge system. This will require close collaboration with other initiatives (especially InterRidge) to ensure coordination of research on selected geologic problems. Drilling, however, can make a number of unique contributions to this effort.

- Drilling is the only way to ground-truth models of crustal structure and composition beneath the seafloor, and to test the geological correspondence of seismic horizons and reflectors.
- Drill cores, complemented with logging data in intervals of poor recovery, provide vertically-

continuous sections in which it is possible to assess the stratigraphic relationships between units, the geometry, vertical extent, and crosscutting relationships of successive sets of magmatic intrusions, hydrothermal veins, and deformational structures. This is of primary importance for a number of issues such as: the fractionation processes and dynamics of axial magma bodies; the kinematics and distribution of deformations; the interplay of deformational, hydrothermal and magmatic processes in the lower crust and upper mantle; and the episodicity of volcanic eruptions at a single location (by counting the number of individual lava flows in a given time interval). Furthermore, through precise age dating it may be possible to develop true age-related stratigraphic sections, to assess the importance of off-axis volcanism and intrusion, and to determine the length of time required to develop the characteristic litho- and magnetostratigraphy that is generally observed. In addition, coring can provide constraints on timing of uplift and subsidence by recovering stratigraphic sections from sedimented fracture zones, including those where the topographic highs once extended to the ocean surface and therefore include carbonate caps.

- Drill holes can be used for borehole logging, downhole experiments and long-term geophysical monitoring. They are an essential component of the ocean bottom observatory concept. Downhole geophysical experiments in two or more closely spaced drill holes may also prove to be a unique way to assess the small-scale heterogeneity of the oceanic lithosphere. Such experiments must be designed so as to characterize both the tectonic sources of heterogeneity and those related to magmatic variations.
- The physical and chemical evolution of oceanic crust is a subseafloor process that can only be addressed by drilling. The evolution of the oceanic crust results from the time-integrated superposition of a continuum of processes that occur on-axis, near-axis and beneath the sediment cover well away from the spreading axis. Understanding the processes that result in the evolution of oceanic crust therefore requires drilling in several environments that represent different stages of the evolution.
- One important objective of drilling must be to test the hypothesis that fossil hydrothermal systems preserved in ophiolites are a useful analog of the active systems at ocean ridges. However, even if this hypothesis is valid, there are many aspects of magmatic and hydrothermal systems that cannot be determined from an extinct system, including the variations in permeability and porosity of the host rocks, the physical properties and composition of the circulating fluid, the dynamics of the water-hot rock interface, and the processes that control the formation of sulfide deposits.
- Recovering older (> 1 Ma) basaltic crust by drilling can provide important information about temporal and spatial variations in upper mantle composition and the processes responsible for generating ocean ridge basalt melts. Drilling can make two important contributions. First, drilling can provide a continuous, high-resolution record of the history of magmatic activity at one location on a time scale shorter than that of the construction of Layer 2 (10^5 to 10^6 years). This type of vertical stratigraphy, which is unavailable from surface sampling (e.g., dredging, rock coring), permits evaluation of short-term variations in the magmatic budget and mantle chemistry at a single location. Second, drilling and recovering older oceanic crust can provide constraints on the temporal variability of the mantle on time scales of 10^6-10^8 years.

Drillholes can also be used to expand the Global Seismic Network to include ocean-bottom seismic stations located in drill holes to improve the resolution of tomographic studies of the upper and lower mantle. One such hole has already been drilled off the coast of Hawaii specifically as part of this program.

A.5 Drilling Strategy and Priorities

A.5.1 Magmatic and Tectonic Processes

1. Sampling of upper crust. Many of the above questions concerning ocean ridge magmatic and tectonic problems can be best addressed by drilling young (< 1 Ma) oceanic crust to depths of only a few hundreds of meters or less. In order to achieve many of the near-axis drilling objectives, including drilling through a magma chamber seismic reflector and the installation of natural laboratories on the seafloor, will require further development of a bare-rock drilling system such as the DCS. Without such a system, deep (100-500 m) penetration and recovery of young and highly fractured upper oceanic crust probably will be impossible. Hence, the highest engineering priority of LITHP is the continued development of DCS. LITHP clearly recognizes that this endeavor will require a substantial commitment of ODP resources. However, without a bare-rock drilling capability many upper crustal drilling objectives cannot be accomplished with the present drilling technology.
2. Sampling of the lower crust and upper mantle. The best constraints on processes below the upper crust will come from direct samples of rocks formed at those depths. Two strategies exist for sampling such rocks:
(1) moderate-depth holes in tectonic windows that have exhumed lower crust and mantle

rocks, and (2) deep drilling of unextended lithosphere. For the near future, the greatest returns will come from moderate-depth holes in tectonic windows, following strategies outlined in the Offset-Drilling Working Group Report. Recently drilled Hess Deep sites are examples of the offset-section drilling approach and provide valuable data on processes occurring in a fast spreading ridge magma chamber and crust-mantle transition. Drilling in the MARK area, in the Atlantic, followed a similar strategy and helped characterize processes of crustal formation and emplacement of upper mantle rocks at a slow spreading ridge. These results should complement the lower crustal sections already available from drilling at Site 735B.

For the long term, there are advantages to very deep holes reaching the lower crust and mantle in unextended areas of thick upper crust because it appears that such areas are characteristic of a large proportion of the lithosphere created at mid-ocean ridges, especially at fast and intermediate spreading rates. In such areas, deep drilling is the only way to characterize crustal and upper mantle processes, with no interference from superimposed extension linked with the formation of tectonic windows.

A.5.2 Hydrothermal Processes

The primary goal of a ridge-crest hydrothermal drilling program should be the establishment of a 1000+ m, high-temperature reference hole in an active hydrothermal system. The target should be the penetration of the boundary between a vigorous hydrothermal system and an identifiable heat source (or at least the magma chamber reflection) which may require at least 2000 m of drilling. The physical and chemical properties, and the thickness and dynamic behavior of this boundary are completely unknown, yet they control the style and vigor of heat and mass transport within the magma chamber as well as that of the surrounding hydrothermal system.

Another goal of a hydrothermal drilling program should be to examine along-axis and across-axis variations within a single ridge segment. Along-strike variations include at least two scales of investigation, the segment scale (10s of kilometers) and the scale of individual on-axis hydrothermal circulation cells (size uncertain, but probably of the order of 0.5 to 4.0 km).

A third goal of a long-term hydrothermal drilling program should be to investigate the fundamental differences between hydrothermal systems at sedimented and sediment-free spreading centers.

Finally, drilling seafloor hydrothermal systems must take into account the positioning of drill holes and arrays of drill holes to optimize post-drilling experiments. For example, seismic and electromagnetic tomography from boreholes, together with multi-channel seismic imaging of the roof of the magma chamber, promise to provide important physical constraints on key components of submarine hydrothermal systems. Implementation of a borehole seal (CORK system) permits time-series fluid sampling and long-term monitoring of properties such as temperature and pressure.

A.5.3 Fracture Zone and Transform Fault Processes

Transforms on fast spreading ridges may be fundamentally different than those on slow spreading ridges. Therefore, a drilling program needs to include features of transforms within both types of settings. A high-priority for the short term should be to drill a series of holes at a transform fault on a fast-spreading ridge. It is also desirable to drill fracture zones away from the mid-ocean ridges since they may provide the major conduit for continued hydrothermal circulation, perhaps ongoing volcanism and ongoing (perhaps aseismic) tectonism in older crust.

A.5.4 Physical State and Evolution of the Lithosphere

Reliable in situ stress measurements can now be made in drill holes by using stress-induced borehole breakouts and acoustical imaging logging tools. Determining the stress regime at a mid-ocean ridge would involve drilling a series of holes that penetrate 500 m into basement located in a number of relatively closely-spaced (<1 km to tens of km) arrays or transects along and across the ridge crest. These should be augmented with detailed physical property and borehole studies that would help define the kinematics of brittle crustal deformation and the physical properties of the crust.

One profound geophysical change in oceanic crust with increasing age is the velocity increase in Layer 2A, and its eventual merger with Layer 2B. Therefore, the uppermost oceanic crust is a high-priority drilling target. An ideal experiment would drill a time transect along a flow line of oceanic crust that had a simple and constant history that could extrapolated to "typical" oceanic crust. Questions about Layer 2A require holes penetrating at least to seismically-resolved thicknesses (200-600 meters).

A.5.5 Structure and Scale of Compositional Variability

The fundamental questions concerning temporal and spatial heterogeneity of the oceanic crust and upper mantle can be addressed by systematically drilling off-axis holes, with 100 meters or more of basement penetration, both parallel and perpendicular to the ridge axis within a regional context. The number and pattern of spacing of these drill sites will depend on spreading rates, ridge morphology, segmentation, etc. In terms of drilling priorities in regions identified for off-axis "temporal and spatial" drilling, segments should first be structurally and chemically well documented along strike. Both plume and non-plume segments need to be investigated.

A.5.6 Global Seismic Network

Improvement in the resolution of tomographic studies can be achieved by establishing a network of seafloor seismic stations. This will require emplacement in all the major ocean basins with a distribution that will complement the land-based stations of the Global Seismic Network. These stations should be in crustal holes that are 100-200 m deep, and should include both short-period and long-period, broad-band seismometers. This program needs to be carefully coordinated with ODP, as holes drilled for other purposes may be suitable for seismometer emplacement at a later date.

B. Large Igneous Provinces

Large igneous provinces (LIPs) are a continuum of voluminous crustal emplacements of predominantly mafic extrusive and intrusive rock that represent a fundamental mode of mantle circulation. This mode of circulation and igneous activity is commonly distinct from that which characterizes plate tectonics and seafloor spreading, and is observed not only on Earth, but also on the Moon, Venus, and Mars. LIPs include oceanic plateaus, submarine ridges, seamount groups, and ocean basin flood basalts, as well as continental flood basalts and volcanic passive margins. LIPs are the most voluminous accumulations of mafic material on the Earth's surface, other than basalts and associated intrusive rock emplaced at spreading centers. They therefore provide windows into the compositions and dynamics of those regions of the mantle that do not generate normal mid-ocean ridge basalt (N-MORB). They now account for between 5% and 10% of the heat and magma expelled from the mantle. Voluminous fluxes of magma over relatively short time periods have characterized several distinct episodes in Earth history, are commonly associated with ultramafic-mafic magmatism, and may be a principal mechanism for stabilizing crust on the Earth's surface. The ocean basins contain several large plateaus that may comprise future building blocks of continental crust. The magmatic fluxes that built such plateaus, however, are not evenly distributed in space and time; their episodicity punctuates the relatively steady-state production of crust at seafloor spreading centers. These intense episodes of igneous activity temporarily alter the flux of solids, particulates, volatiles, and heat from the lithosphere to the hydrosphere and atmosphere, possibly resulting in global environmental change and excursions in the chemical and isotopic composition of seawater. To account for voluminous magmatism that creates LIPs, two fundamentally different and mutually exclusive models have been proposed. In the "active" plume model, igneous activity is caused when a transient broad mantle plume "head" impinges on the base of the lithosphere and is sustained by a deeper narrow plume "tail" that rises through the thermal wake of the plume head. In the "passive" plume model, lithospheric extension allows a preexisting steady-state mantle plume to penetrate the crust and initiate igneous activity. A third model, which pertains largely to volcanic rifted margins, is that of "secondary convection," in which asthenospheric mantle convectively overturns close to the conjugate trailing edges of preexisting thick and cold lithosphere. Lithospheric plate motion vectors are recorded by persistent volcanism that produces a linear submarine ridge or seamount chain.

B.1 General Questions and Problems

The major objective of LIP studies is to describe and understand upper crustal to upper mantle igneous and deformational processes related to their emplacement, how they relate to deeper mantle processes and dynamics, and how they relate to plate tectonic processes. Generally, LIP crust is buried under as much as 1.5 km of sediment; hence, drilling is in most cases the only method of recovering samples of basement rock. Paleontological evidence from the sediments deposited on the plateaus will provide important constraints on the age of these features and their long-term subsidence history. Drilling of LIPs in different tectonic environments will address questions regarding:

- Behavior of mantle plumes. Do plumes play an "active" or a "passive" role in LIP emplacement? Is there evidence for any plumes to have originated from extraterrestrial impacts? Emplacement environments range from purely extensional (e.g., Iceland) to intraplate (e.g., Hawaii), but the original tectonic setting for many LIPs (including the two giants, Ontong Java and Kerguelen-Broken Ridge oceanic plateaus) remains unknown. Because parental magma of basalts in the two models originates at different mantle depths and follows different time-temperature paths, petrological and geochemical studies of drill core samples and estimates of magma production rates will constrain relative contributions from the two processes.
- Interaction of mantle plumes and lithosphere. How is heat added to the lithosphere and what is the role of volcanoes in raising temperatures? What is the uplift and subsidence history of the LIP, and what are the relative thermal and dynamic contributions of upwelling lithosphere in producing swells? Deep LIP basement (500-1000 m) and sedimentary equivalent (moat) samples, in conjunction with high-quality geophysical data, can constrain: (1) overall timing of the deformation, and (2) relative timing of elastic response from which strain rate, effective elastic thickness of the lithosphere, flexural rigidity, relative importance of lithospheric reheating, and possible lateral flow of material at deeper levels can be determined.
- Deformation and timing of the entire LIP emplacement process. Drilling can provide a vertical stratigraphic record in syn-constructional sediment that constrains absolute and relative ages of uplift, magmatism, and subsidence during LIP emplacement and evolution. Reference holes on older normal

oceanic crust will provide evidence for nature of the initial stages of volcanism. Accurate dating of LIPs, in particular their extrusive components, will provide input for correlations and cause-and-effect relationships with changes in the Earth's magnetic field, true polar wander, and hydrospheric-atmospheric physical and chemical changes. With respect to volcanic rifted margins, drilling can help to resolve whether they develop symmetrically or asymmetrically. Is significant thinning a prerequisite for voluminous magmatism, or is lithospheric deformation a direct consequence of hot asthenospheric material rising to shallow, crustal levels? What is the vertical tectonic history of the seaward-dipping reflector wedge and the earliest oceanic crust?

- Mechanism of magma emplacement. What are the petrological, geochemical, and volumetric characteristics of magmatism, and what is the role of magmatic underplating? What is the duration, rate and episodicity of volcanism and what is the nature of the eruptive style (i.e., are subaerial flows present)? How do LIPs compare with continental flood basalt provinces? Full sampling of the sequence of volcanism by drilling a LIP and its sedimentary equivalents will provide critical information on the petrological and geochemical evolution of magmatism during rifting, and by inference constrain the thermal and compositional evolution of the underlying mantle. Igneous basement samples can provide information on asthenosphere-lithosphere interactions.
- Flux of volatiles and heat from the lithosphere. How do intense pulses of igneous activity associated with LIP emplacement affect the physical, chemical, and isotopic character of the oceans and atmosphere? Can the pulses be correlated with changes in biota, paleoclimate, paleooceanography, paleoenvironment, paleogeography, and sea level, and if so, can causal mechanisms be determined? Is off-axis hydrothermal circulation significantly different than ridge-crest hydrothermal activity? Thermal and permeability structure of old oceanic and transitional crust invaded by LIP heat sources likely differs from mid-ocean ridges. Therefore the products and consequences of hydrothermal activity in this setting may differ significantly. Is oceanic crust underlying LIPs fundamentally altered by this hydrothermal activity and could this contribute to the flux of seawater-derived components back into the mantle at subduction zones?

B.1.1 Oceanic Plateaus

Despite their huge size and distinctive morphology, the oceanic plateaus (e.g., Wallaby, Shatsky Rise, Ontong Java, Kerguelen-Broken Ridge, etc.) remain among the least understood features in the ocean basins. They are characterized by 20-30 km thick crust, with many constructed entirely from some combination of MORB and OIB source magmas, but some composed at least partially of continental crust (e.g., Mascarene Plateau).

The plate setting of emplacement of the two primary classes of oceanic plateaus—those exhibiting persistent and those characterized by transient volcanism—is not defined in many instances. Identification of magnetic anomalies on adjacent oceanic crust and of fracture zone traces are required to determine the plate setting of a plateau. Most oceanic plateaus probably result from some sort of hotspot-type volcanism. The volume of volcanism, erupted over a geologically short time period, indicates a major disturbance of the normal thermal and convective pattern in the mantle, which may imply a connection between plateau emplacement and plate tectonics. The two giant oceanic plateaus, Ontong Java and Kerguelen-Broken Ridge, are of particular interest because of the potential environmental impacts of their emplacements. Major questions, however, still exist concerning the duration, rate, and episodicity of volcanism and intrusion on oceanic plateaus.

Post-emplacement, oceanic plateaus appear to subside somewhat along a thermal subsidence curve. However, dynamic flow in the mantle and resulting lithospheric thinning associated with the formation of the plateaus may lead to departures in the vertical motion history with respect to predictions of the standard thermal plate model. Other processes such as extension, compression, and shear bearing little or no relationship to thermal subsidence models may also affect the vertical tectonic history of an oceanic plateau. More information is needed to determine the temporal and spatial development of post-emplacement deformation, which could provide insight into the stress regime of the plateau. The state of lithospheric stress in the vicinity of oceanic plateaus could be estimated by examining whether deformation preferentially occurs on plateaus as opposed to adjacent oceanic crust.

B.1.2 Transition Between Continental and Oceanic Lithosphere at Rifted Margins

Divergent rifted margins are among the most prominent topographic features on our planet, and they are the primary storehouses of information on continental breakup. The transition from continental rifting to incipient oceanic rifting to recognizable seafloor spreading, however, remains poorly understood. Asymmetric development of continental margins, as embodied in "simple shear" models, is now a viable alternative to symmetric development as characterized in "pure shear" models. Whether pure or simple shear, traditional views that the crust is significantly thinned prior to rifting have been contradicted by recent seismic reflection studies that show that many rifted margins are characterized by voluminous magmatism. Volcanism, commonly observed as, but not limited to, seaward dipping reflector (SDR) wedges, volumetrically exceeds that in most Phanerozoic continental rifts, and crust thickens at the ocean-continent transition (OCT).

Two other classes of margins need to be examined to understand continental rifting and its underlying processes. In one case, increasing evidence suggests that mantle plumes are not associated with voluminous volcanism along some margins. Such margins should be investigated for contrast and comparison with margins dominated by large mantle plumes. In another case, rift development and the formation of the ocean-continent transition are best studied by drilling juvenile ocean basins. Unique magmatic and hydrothermal systems in such nascent basins are ideally examined before they are buried by later passive margin sequences.

B.1.3 Seamounts and Submarine Ridges

Hotspot volcanism generates submarine ridges and seamount chains, some of which are clearly built on older oceanic crust as the plate moves relative to the hotspot. However, important questions regarding the coincidence of the ridge and the hotspot and its long-term maintenance still have to be resolved. Such features are of considerable lithospheric interest both for the constraints they place on plate kinematics and absolute plate motions, and as a means of investigating the composition and geochemical evolution of the mantle, particularly during the early stage of volcanism.

Mid-plate volcanism represents a thermal perturbation to the cooling lithosphere that can be exploited as a natural laboratory to study the thermal-mechanical properties of the oceanic lithosphere. The thermal anomaly associated with mid-plate volcanism appears to form a broad region of shallow seafloor before significant emplacement of extrusive or intrusive material in the crust. During and after emplacement, the thermal regime of the lithosphere continues to be perturbed, and through time the composition of the magmas reflect the thermal history of the underlying mantle. Ultimately the constructional phase ends and subsidence begins. Most of the characteristics of swells can be explained by the reheating of the mid- to lower lithosphere. However, there is no consensus as to the mechanism by which the heat is added to the lithosphere, the role played by the volcanoes in raising temperatures, or the dynamic contribution of the upwelling asthenosphere in producing swells.

B.2 Contributions From Drilling

The major objective of LIP studies is to describe and understand upper crustal to upper mantle igneous and deformational processes related to their emplacement, how they relate to deeper mantle processes and dynamics, and how they relate to plate tectonic processes. Generally, LIP crust is buried under as much as 1.5 km of sediment; hence, drilling is in most cases the only method of recovering samples of basement rock. Paleontological evidence from the sediments deposited on the plateaus will provide important constraints on the age of these features and their long-term subsidence history. Because of the abundant supply of terrigenous sediments at developing oceanic rifts, the volcanic products of early rifting are also usually deeply buried and the sediment section extensively injected with sills. Drilling is therefore the only way to sample this crust.

B.3 Drilling Strategies and Priorities

Our drilling strategies address the initiation, emplacement, and post-emplacement phases of LIP evolution, and the role of these provinces in crustal evolution. The principal drilling strategy for LIPs would be based on transect sampling, supplemented by holes of opportunity. A drilling transect would normally consist of a series of holes sampling key igneous, sedimentary, and metamorphic rock units, tied to reference holes in normal oceanic crust. Moderately deep (500-1000 m) basement penetration should be achieved to establish the uppermost igneous stratigraphy. All drill holes should be continued at least 150 m into the igneous basement to constrain its age, petrology, and geochemistry, and to sample geomagnetic field behavior.

B.3.1 Oceanic Plateaus

Two transect drilling strategies are recommended:

1. The first is to drill longitudinal, latitudinal, and offset transects of the two giant oceanic plateau provinces—Kerguelen-Broken Ridge or Ontonga Java-Manihiki—together with reference holes in the adjacent oceanic crust. At a minimum, this would involve one site per 100,000 km^2 (i.e., Iceland-size), with at least one site having basement penetration of about 1 km, in order to test for composition and age variations. The longitudinal transect would be drilled normal to magnetic lineations on the adjacent oceanic crust. Offset holes, drilled where rifts expose rocks from deeper crustal levels (e.g., Manihiki or Kerguelen-Broken Ridge), would allow construction of a composite igneous stratigraphy for the upper crust, and would help constrain the emplacement duration of volcanism. Reconnaissance drilling of each giant plateau province has provided the first samples for age, petrologic, and geochemical analyses, and has set the stage for more problem-oriented studies. ODP Legs 119, 120, and 130 represent the beginning of such a strategy.
2. The second strategy is to drill longtiudinal and latitudinal transects on a plateau of purely oceanic origin—e.g., Manihiki, Shatsky, Hess, or Wallaby—which represents one end-member in crustal composition. Minimal areal coverage should be the same as for the giant oceanic plateaus, resulting in about 5 sites, not including reference holes. Uplift and subsidence history could be addressed by drilling the oldest reef-capped volcanoes within a given LIP.

B.3.2 Rifted Margins

Two implementations of the transect strategy on volcanic rifted margins are proposed:

1. The first is to drill a series of holes beginning at a plume locus and then along the strike of a single or conjugate volcanic passive margin(s) in order to evaluate temporal and spatial involvement of the plume with continental breakup. At least one hole should be drilled in each margin segment bounded by major fracture zones away from the plume locus. Such a strategy would allow testing of "active" and "passive" plume models and the secondary convection model. ODP Legs 104 and 152 represent the beginning of such a strategy.
2. The second strategy is to drill transects across conjugate volcanic passive margins in order to test pure and simple shear models of lithospheric deformation, and to examine the role and temporal evolution of accompanying magmatism. Implementation of this strategy has not yet commenced.

Drilling on volcanic rifted margins should be complemented by studies of margins away from the large volcanic plumes. Recent geophysical measurements have suggested that volcanism can be an important component of margin development, even away from large plumes, and a sampling of the range of rifted margins types is necessary if we are to understand the mechanisms of continental break-up and provide a template to help us understand volcanism in incipient rifts like the Red Sea and East African Rift.

B.3. 3 Seamounts and Submarine Ridges

Drilling strategies for seamounts, because their igneous basement is more accessible to dredging, and in many cases to onshore drilling, will vary widely depending on specific scientific objectives. As an example, the early evolution of plume magmas, in particular temporal relationships of alkalic and tholeiitic volcanism, source composition, degree of partial melting, fractionation history, and lithospheric contamination, might be studied through intensive sampling of a young seamount. The volcanic and structural evolution of intraplate volcanoes can also be examined by drilling the volcaniclastic aprons surrounding them. Those aprons include a record of both the eruptive products of the volcano from its inception and the vertical movements of the edifice and its surrounding oceanic crust.

C. Convergent Margins

Convergent margins comprise three tectonic units—forearcs, volcanic arcs, and backarc basins. The tectonic and magmatic character of these three provinces are linked, and understanding any of the three requires an understanding of the convergent system as a whole. Convergent margins are of interest to the lithosphere community in two important ways:

- These margins are an important part of global geochemical cycles. Subduction of the oceanic lithosphere is a fundamental part of the mantle's convection cycle and arc and backarc magmatic activity are important contributors to the chemical evolution of the mantle. Alteration and dewatering reactions in the downgoing slab are part of hydrospheric and atmosphere cycles, and may have a profound influence on the structural and magmatic evolution of forearcs.
- The oceanic crust constructed and modified at convergent margins is that most likely to be preserved in the geologic record. The recognition that many ophiolites form in supra-subduction zone environments—forearcs, arcs, and backarc—indicates the need to study oceanic crust in these environments.

The lithosphere community's objectives at convergent margins can be discussed broadly in terms of the problem of quantifying geochemical fluxes. That quantification requires knowledge of lithosphere structure and composition, fluid processes, and magmatic variability in space and time. All of these topics are related—understanding any one requires some understanding of the others.

The quantification of geochemical fluxes through the lithosphere is one of the long-standing objectives of ODP. These fluxes, in the broadest sense, include low-temperature fluid fluxes in forearcs, hydrothermal reactions in arcs and backarcs, magmatic transfer of material from the sub-arc mantle, and return of components to the mantle through the subduction and melting or dewatering of the subducting slab. Understanding the pathways involved in convergent margin geochemical fluxes, and more importantly, quantifying the transport in each of those pathways requires the examination of entire convergent margin systems, from the downgoing plate, through the forearc and arc, to the backarc and its associated magmatic and hydrothermal systems.

C1. Lithosphere Composition and Structure

One part of understanding geochemical fluxes requires unraveling the distribution of rock units within the convergent margin lithosphere. Understanding that distribution must begin with the material being carried into subduction zones on the outboard plate. Both the sedimentary sections and the underlying, altered oceanic crust may be important contributors to fluid flow and magmatism in the convergent margin system. Recent studies of existing oceanic sediments show a striking correlation between the incoming sedimentary section and the concentration of some geochemical tracers in arc lavas. More carefully crafted experiments are needed to constrain the links between what is entering trenches and what is observed in fluid and magma flow in the upper plate. These mass balances may be most easily accomplished at intraoceanic arcs, which lack the complexities of margins with thick, ancient continental crust adjacent to the subduction zone.

Forearc tectonics play a crucial role in geochemical mass balances in subduction systems. The forearc structure and sedimentary sections record the history of sediment subduction or accretion and of subduction erosion. It is necessary to understand not only what is currently happening at these margins, but what has happened, and at what rate, in the past. Much of the dewatering of the plate must occur as it passes under the forearc; this dewatering will be manifest in fluid flow and metamorphism in the forearc. Convergent margin forearcs also record three important aspects of volcanism in convergent margins. First, there is growing evidence that many forearcs are floored by voluminous arc volcanics produced early in the development of the subduction zone. However, there is no clear idea of how much of the forearc crust is older, trapped ocean crust and how much is newly produced arc crust. Second, the only record of arc volcanism from its inception to the present is contained within forearc basin sediments.

The evolution of the arc itself has been addressed directly only at a few sites. The volcanologic or chemical evolution of single arc volcanoes and of the hydrothermal systems associated with them are poorly understood. The arc volcanoes play an important part in both the high-temperature igneous geochemical fluxes in the margin and the lower temperature hydrothermal interactions with seawater. One of the most significant gaps in our ability to understand chemical fluxes in convergent margins is our lack of understanding about the nature of geochemical changes within individual arc volcanoes.

Finally, many convergent margins include an actively spreading backarc basin. Recent studies have shown that these backarc systems share many features in common with their counterparts in larger ocean basins, including spreading geometries, development of propagating rifts, and the development of robust hydrothermal systems. However, there is also evidence that the lavas in these basins are compositionally more diverse than those in large ocean basins, ranging from compositions indistinguishable from arc lavas to those approaching normal mid-ocean ridge basalts. The diversity of volcanism in time and space indicate a complex distribution of sources beneath the basins. We have, as yet, only a limited knowledge of the systematics of the variations in backarc lava chemistries and the consequence effect on the nature of hydrothermal systems and of the real differences between mantle beneath the arc and that beneath the backarc basin. Some models are beginning to emerge for the nucleation and evolution of backarcs, particularly in regard to the amount of extension accommodated by stretching of the lithosphere.

C2. Fluid Processes

The evolution and migration of fluids in the lithosphere is one important part of geochemical cycles in convergent margins. Fluid processes include flow due to the dewatering and dehydration of the subducting plate and hydrothermal reactions at arc and backarc volcanic centers.

The composition and flow of fluids derived from the subducting slab will depend upon the nature of the material entering the trench, the thermal regime beneath the forearc and arc, and the rates of dewatering and dehydration. Much of the fluid flow will occur beneath the forearc, from dewatering due to compaction and from low-temperature dehydration reactions. The record of this fluid flow is manifest in active venting of forearc fluids, as observed in several forearcs, and in the nature of metamorphic reactions recorded in forearc rocks. The record of this fluid flow is complicated by the superposition of reactions due to circulating seawater. The recognition of young igneous activity in some forearcs emphasizes the possibility of active hydrothermal circulation even in apparently "cold" forearcs. Quantifying the fluid flow through the forearc requires an examination of the offshore crustal section and the vertical stratigraphy of altered forearc crust.

The dehydration of the slab at depths beneath the arc or backarc can only be examined by looking for the evidence of that dehydration in the magmatic products of the arc or backarc volcanoes. Spatial or temporal evolution of convergent margin magmas may in part be linked to changes in this fluid component.

The second class of fluid processes at convergent margins, hydrothermal flow, can be examined directly by drilling. Both arc and backarc volcanoes develop robust hydrothermal systems. We are only beginning to understand the dynamics of mid-ocean ridge hydrothermal systems, and have, as yet, little knowledge of the differences that characterize backarc or arc hydrothermal circulation. However, convergent margin hydrothermal deposits may be more likely analogs for many on-land ore deposits than are mid-ocean ridge systems, and we need to quantify their abundance, chemical diversity, and fluid flow in much the same manner as for mid-ocean ridge hydrothermal fields.

The local tectonic features of ridge formation and rifting in backarc environments are similar to those of mid-ocean ridges, the major difference being that backarc rifts are developing in oceanic crust above a subduction zone. In some cases, backarc rifting may occur in fragments of continental crust close to continental margins (e.g., Okinawa Trough, East China Sea). Hydrothermal systems forming at backarc rifts also display many similarities to those at the mid-ocean ridges. The composition of fluids and hydrothermal precipitates, however, is a consequence of the host rock lithology. Sulfides in immature backarc rifts or in rifted arcs are commonly associated with lavas that are more siliceous than those normally found on the mid-ocean ridges and are usually enriched in elements such as Pb, As, Ag and Au. In contrast, massive sulfides forming in more mature, basalt-dominated, backarc rifts have a composition that parallels that of mid-ocean ridge sulfides. Drilling into hydrothermal systems is the only way to investigate in situ interaction of seawater with felsic lavas and to determine possible contributions of subduction-related magmatic fluids.

C3. Magmatic Variability in Space and Time

The magmatic activity at convergent margins produces the record from which we must determine the fluxes of elements from the mantle to the crust, from the subducted slab back to the crust, and by difference from the subducted slab back into the mantle. Understanding the origin of arc and backarc volcanism requires identifying the characteristics of that magmatism which are process-related and those which are source-related. One of the only ways to separate these factors is to examine the spatial and temporal variability in magmatic products in an attempt to isolate single processes or sources. Systems with both backarc and arc volcanism are particularly suited to this approach as they provide spatially and temporally parallel records of differing composition. Drilling becomes an essential tool in examining this problem, because of the limited accessibility of many parts of the convergent margin basement and because of the importance of vertical sections through the crust.

Drilling to date in the western Pacific has led to a reexamination of long-standing models for the evolution of arc volcanoes. Arcs show a diversity along and across strike from tholeiitic to shoshonitic that are as profound as the long-term temporal changes. The contribution of subducted sources, mantle sources, and arc rifting to this diversity is as yet unknown. Rifting and re-establishment of arc volcanism are clearly the most prominent non-steady state phenomenon in convergent margins, but the arc lavas do not show consistent changes through these rifting events at different times and in different arcs. Low-K rhyolites, boninites, and shoshonites have been recognized as important components of different arcs at different times, but the patterns in their distribution and their significance in piecing together the importance of source vs. process in the composition of arc magmas is as yet unclear. DSDP and ODP drilling has shown the utility of ashes and vitric turbidites in constraining the long-term evolution of the arc—in fact, these sedimentary records are really the only way to define the long-term changes in the arc.

One of the most striking findings of western Pacific drilling in intraoceanic convergent margins has been the recognition that the earliest volcanism associated with intraoceanic subduction produced voluminous volcanic constructs with different morphologies and compositions than the later developed arc edifices. These early arc constructs are now preserved in the forearcs of intraoceanic systems and have striking petrologic, structural, and geochemical similarities to many ophiolites.

This model of early arc volcanism derives principally from work in the Izu-Mariana-Bonin system. Drilling, dredging, and island studies have documented a middle to late Eocene arc complex 200 to 300 km wide and 2000 km long. This crust was the first constructed as a consequence of subduction in the Izu-Bonin-Mariana system and developed at eruption rates more like those of slow-spreading ridges than of modern arc volcanoes. The identification of dike complexes is some forearc islands (Chichijima) and the absence of any preexisting oceanic crust suggests that the construction of this arc crust proceeded by rifting and spreading. This early arc massif is very similar to ophiolites like those in Troodos and Oman in the abundance of depleted arc tholeiites or boninites, the abundance of cumulate orthopyroxene in norites and gabbronorites, and the highly depleted natures of associated residual peridotites. The early arc crust has become the forearc to the later developed linear arc crust and records in its overlying sedimentary section the history of subsequent arc volcanism and the history of forearc uplift and subsidence as subduction erosion and accretion waxed and waned.

The identification of these voluminous early arc constructs is a radical addition to models of arc development and initiation. These early arcs also provide one of the best analogs for a true supra-subduction zone ophiolite and bear a number of morphologic and petrologic features in common with many.

Drilling in backarc basins of the Pacific has identified the importance of distributed extension vs. seafloor spreading. Different types of volcanism contribute to each stage and range from pure arc end members to nearly pure mid-ocean ridge type end members. There is now sufficient information on these basins to develop detailed tests for models of the transition from arc volcanism, to volcanism associated with rifting, to backarc basin volcanism. Quantification of the distribution and pattern of various backarc components is a critical part in the construction of a convergent margin geochemical balance. Drilling in backarc basins of the western Pacific have suggested that a number of these basins have developed by propagation away from large strike-slip zones.

C.4 Contributions From Drilling

Convergent margins consist of linked tectonic and magmatic units. Any study of a part of these systems, with the goal of understanding the construction or evolution of the lithosphere, needs to address the links between the drilled part of the system and its associated forearc, arc, or backarc. Drilling serves a unique role in convergent margin studies, as it is the only technique that can obtain two critical types of information:

1. The thick sedimentary accumulations of convergent margins typically make drilling the only way to obtain samples of basement,

and consequently the only way to constrain the age of that basement.

2. Arcs differ from spreading ridges in that they are relatively fixed through time, producing vertical accumulations of material to a much greater degree than do ridges. This means that vertical sections of convergent margin crust are essential for quantifying geochemical fluxes, for examining temporal records of magmatic activity (recorded in tephra), and for deciphering temporal records of tectonism (as evidenced in uplift, subsidence, and deformation histories). Drilling provides the only way to constrain the long-term evolution of arcs through the vertical stratigraphy of ashes, turbidites, and lavas. It also provides one of the only ways to develop a quantitative understanding of the nature of geochemical change within individual arc volcanoes. Drilling of arc volcanoes is likely to be most successful in deeper submarine edifices, which have less coarse volcaniclastic debris than shallow or subaerial centers.

C.5 Drilling Strategies and Priorities

There is a tremendous range of problems that can be addressed by drilling at convergent margins, but there are a few problems that have emerged from recent studies as of first-order importance. These four high priorities for drilling along convergent margins are: (1) fluid and solid mass balances in accretionary and non-accretionary margins, (2) the history and causes of subduction initiation and incipient arc volcanism, (3) the development of backarc basins, and their role as a site of ophiolite formation, and (4) the origin and evolution of felsic-hosted massive sulfide deposits.

C.5.1 Mass Balances at Subduction Zones

The balancing of the mass flows at convergent margins has been a priority of the lithosphere community in both the COSOD I and COSOD II plans. There has not, however, been significant progress towards realizing that goal. Drilling is only one part of a program to quantify the flux of material through a convergent margin system, but it is a critical one because it provides a temporal and stratigraphic record. A drilling program to constrain the mass fluxes at a convergent margin should be integrated with a program of structural, physical properties, geochemical, and geophysical studies, and at a minimum should include a study of an accretionary margin and a non-accretionary margin. These transects need to include sites on the offshore plate, to characterize the incoming crust, and sites along a transect across the forearc and arc to provide information on the flow of materials through the forearc wedge. These transects need to be done at margins that have been well-characterized geologically and geophysically, so that the compositions and production rates of the associated arcs and backarcs are well known, or can known with additional, focused studies. The interpretation of these experiments would be simplified if the transects were across margins with relatively simple chemistries in their associated arc volcanoes.

C.5.2 Subduction Initiation and Early Arc Volcanism

A test of this model requires identification of a drilling experiment to constrain basement ages, compositions, and geographic distributions in a well-characterized developing or mature arc system. Mature intraoceanic arc systems appear to leave their initial record as crustal fragments buried beneath forearc sediments; these rocks are accessible in most places in the forearc basins. A test of this hypothesis requires a drilling array that brackets the distribution of the early arc crust—at a minimum, four holes, two pairs of sites spaced across the forearc (of the pair at the frontal arc and the other at the trench slope break) and separated laterally by several 100 km parallel to the trench. These sites should include a substantial sedimentary section, to constrain the tectonic history of the forearc crust, and at least 100 m of basement penetration to examine the chemical characteristics of the early arc volcanism. This volcanism should reflect the characteristics of the mantle before there has been significant modification by the downgoing lithosphere.

A drilling experiment in a developing arc system first requires the identification of a system in which an arc is in the earliest stages of evolution and is volcanically active. Appropriate places might be the northern end of the Luzon Trench or the Macquarie Ridge.

A drilling program to examine the development of early arc volcanism will also address two other important aspects of convergent margin lithospheric evolution. The sedimentary section overlying the forearc volcanic basement is the most complete record of changes in arc composition with time. This sedimentary record also documents the history of tectonic motions in the forearc after the development of the basement. This tectonic history reflects a changing balance in the system between subduction erosion, accretion, serpentine diapirism, and thermal equilibration. A drilling study in intraoceanic forearcs would also document the extent of later forearc volcanic flows, dikes or sills intruded within forearc basin sediments. Drilling in the Tonga, Mariana and Bonin forearcs have all encountered young volcanic rocks with the forearc basin that document at least local episodes of reheating. An important part of any arc or forearc drilling program would also be the retrieval of oriented sediment and basement cores to expand the paleomagnetic constraints on the plate geometries within which arc initiation occurred.

C.5.3 Backarc Initiation and Source Evolution

Drilling in the Japan Sea and Lau Basin has shown that both basins nucleated along a major strike-slip boundary and propagated away from that boundary, splitting the active arc as it went. This work also showed that these basins develop first by a stage of crustal stretching with distributed volcanism, followed by true seafloor spreading with volcanism centralized at the newly created microplate boundary. This model of backarc basin evolution allows predictions to be made regarding the relationships between backarc kinematics, structural styles, and temporal and spatial variations in petrology and geochemistry. This model needs to be tested and refined through investigations of other backarc systems, including those with histories and settings distinct from the Japan Sea and Lau Basin. In particular, drilling in backarc basins should test the timing of backarc development, the associated vertical uplift or subsidence, and the fine-scale compositional changes associated with the rifting of an arc and subsequent re-establishment of a new arc. Multiple transects of drillholes will be required to achieve these goals.

Drilling transects in backarc basins should test the timing of backarc development, the associated vertical uplift or subsidence, and the fine-scale compositional changes associated with the rifting of an arc and subsequent re-establishment of a new arc. Experiments in backarc basins should include two transects, one longitudinally from the terminus of the basin towards its its center, to test the synchroneity of opening, to examine the earliest stages of rift opening and to establish the age of that opening, and to constrain the vertical motions and volcanic activity associated with that opening. A second transect laterally along the basin is required to establish the rate of basin opening and the age progression.

Much of the backarc basin drilling to date has been in the Lau and Mariana systems, both of which are well-developed intraoceanic systems. Further drilling in backarc basins could include either a specific test of the models for basin opening by propagation in those western Pacific systems, or could provide a contrast to such models by drilling in basins at which a different tectonic style may dominate.

C.5.4 The Origin of Arc-Related Ore Deposits

The attention of the seafloor hydrothermal community has been focused for the last decade on mid-ocean ridges because the discovery of active high-temperature hydrothermal venting provides a natural laboratory for investigating the genesis of massive sulfide ore deposits. While the hydrothermal and geochemical processes operative at mid-ocean ridges have general applicability to the formation of massive sulfide deposits formed in a range of environments, the Cyprus-type massive sulfides that are most analogous to ridge-crest sulfides account for a small proportion of the worlds metal production. In contrast, volcanogenic massive sulfide deposits associated with convergent margins (Noranda-type and Koroko-type deposits) include some of the largest and highest grade deposits known. Association with a more diverse suite of volcanic rock types results in a diverse suite of metals in these deposits, including economic concentrations of Cu, Zn, Pb, Sb, Ag, and Au. Modern analogs of these deposits are poorly explored but will be important targets for scientific drilling in the future.

Several other types of ore deposits occur at convergent margins including porphyry Cu deposits, polymetallic vein and replacement deposits, and mesothermal and epithermal precious metal deposits. Epithermal precious metal deposits and Au-depositing hot spring systems are known from the island parts of the Pacific arcs. These systems must be present off-shore and there is likely a transition from meteoric water-dominated to seawater-dominated hydrothermal systems. Scientific drilling will eventually be required to characterize these environments, and ODP is poised to be an important part of this effort. Unresolved problems in understanding the genesis of porphyry Cu deposits parallel the questions about arc magmatism in general. What are the relative contributions from subducted and mantle sources? To what extent are the economic concentrations of Cu, Mo, and Au dependent on the magma source region relative to post melting reactions? Drilling targets in the arc environment of importance to the economic geology community will not only present new opportunities for ODP to pursue important scientific issues, but will also provide the program with new opportunities to attack problems with important relevance to society.

Appendix 1: Lithosphere Drilling Objectives and Accomplishments: 1981-1993 (*see pages 23-25*)

Left-hand two columns list legs addressing thematic problem outlined in COSOD I and II. Right-hand columns list legs directed at specific goals or strategies as listed in various White Papers and in the *Long Range Plan*

Appendix 1: Lithosphere Drilling Objectives and Accomplishments: 1981-1993
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Thematic problems	Legs addressing those problems (**successful legs devoted to principal lithosphere objectives;** *legs partially successful or making secondary contributions to lithosphere objectives;* [minor contributions to lithosphere objectives])	Specific Goals of Long Range Plan or *Drilling Strategy* (2)--# of legs suggested for goal	Legs Addressing Strategies or Goals *Important Technical Advances*
[1]**Architecture of the ocean crust and the ophiolite model; nature of seismic layers and transitions; composition of Layer 3**	*Leg 109-MAR peridotites* **Legs 111, 137, 140, 148-504B** **Leg 118-500 m gabbro, Indian Ocean** **Leg 147-Hess Deep, Layer 3, "Moho-like" section** **Leg 153-MARK area, lower crust and mantle**	*offset section drilling* by 1997 drill three 2-3 km holes one each in fast, slow, thin crust (4) by 1993 deepen 504B (2) extend one hole to Moho (6)	Legs 109, 118, 147, 153 *Development of hard-rock guide base* Legs 111, 137, 140, 148 for > 2 km
[1]Ocean ridge processes			
crustal accretion processes at slow and fast ridges	*Legs 106/109-basalt* *Leg 142-EPR I-basalt*	*drill arrays of of 300 m and 1-1.5 km holes in fast, slow, and sedimented ridges; one of these instrumented as sea-floor lab by 2000*	*Leg 106 HRB and unsupported spud-in* *Leg 124E DCS test* *Leg 132 DCS test* *Leg 139-high temperature drilling and CORK deployment* *Leg 142-drill in casing*
hydrothermal processes at bare rock slow and fast ridges,	*Leg 109-Snake Pit sulfide deposits* *Leg 158--TAG hydrothermal area*		
hydrothermal systems at sedimented ridges	**Leg 139-JDF, Middle Valley sulfides**	by 1993 begin sedimented and fast spread arrays (4)	Leg 142 EPR I Leg 139-Juan de Fuca, Middle Valley
along and across strike variation in magmatic and hydrothermal processes	*Logging of Sites 684, 395A, 418A*	by 1997 finish fast spread array, start slow spread (4)	
contribution and significance of near-axis seamounts*	*Leg 129--Site 801C--off-axis modification of crust*		
temporal evolution of ridge crest processes			
natural laboratories and long-term monitoring	**Leg 139-CORKs at Middle Valley**		
Initiation of oceanic basins			
Rift styles and mechanisms in young ocean basins	*Leg 139-sedimented ridge crustal structure*	*Red Sea, Gulf of California transects*	
Styles of rifting in passive margins and controls on the development of volcanic vs. non-volcanic margins	*Leg 103 Galicia Bank* **Leg 104 Voring Plateau (volcanic)** *Leg 122/123 Exmouth Plateau* *Leg 149-Iberia Margin* *Leg 152-E. Greenland margin* *Leg 107 Tyrrhenian Sea*	By 1997 drill rifted conjugate margins, volcanic and non-volcanic	Leg 103 Galicia Bank Leg 104 Voring Plateau Leg 149 Iberia Margin Leg 152-E. Greenland margin

Thematic problems	Legs addressing those problems (**successful legs devoted to principal lithosphere objectives;** *legs partially successful or making secondary contributions to lithosphere objectives;* [minor contributions to lithosphere objectives]	Specific Goals of Long Range Plan or *Drilling Strategy* (2)--# of legs suggested for goal	Legs Addressing Strategies or Goals *Important Technical Advances*
Fracture zone effects on lithosphere construction and evolution	*Leg 118-some intra-fracture zone drilling* Leg 157-Vema transverse Ridge, DCS test		
Composition and controls on intraplate volcanism			
composition of early eruptive products (e.g. Loihi)		*deep hole in representative seamount*; arrays of shallow holes*	
basement ages and compositions along linear volcanic chains	[Leg 113-Maud Rise age and basement] [Leg 114-Meteor and Islas Orcados Rises] *Leg 143/144 Pacific Atolls and guyots* **Leg 121-Broken and Ninety-East Ridges**	drill in hotspot chains (2)	Legs 115 and 121
age and composition of oceanic plateaus	**Leg 115-Mascarene Plateau and Reunion** *Legs 119/120 Kerguelen Plateau* *Leg 130-Ontong-Java Plateau*	drill oceanic plateaus (1)	Legs 119, 120, 130
timing of oceanic plateau development			
Timing of uplift and evolution of swells around intraplate highs; flexural strength of lithosphere	*Leg 136-Hawaiian arch (for OSN test)*		
Aging and evolution of oceanic crust			
Ridge flank hydrothermal activity	*Leg 111--rise flank flow, near 504B*	*logging of all deep holes*	
Porosity/permeability evolution Causes of changes in seismic character with age	**Leg 102-logging 418A** **sampling and logging at 504B** **Leg 109-logging Site 395A** *Leg 129-Old Pacific crust, 801C* *Leg 144-logging 801C*	*several deep holes in old sedimented crust* refine Mesozoic magnetic dating in Pacific (1)	Leg 129-Site 801C
Mantle dynamics and plate kinematics and lithospheric stress	Leg 136--test site for OSN-1 *Leg 116-Bengal fan, intraplate compression* *all sites with significant recovered basement contribute to geochemical mapping of the mantle*	develop and test downhole seismometer (1) by 1997 deploy 6 OSN stations (2 stress measurement in specific settings (1) intraplate compression-extension studies (2 legs by 1997)	Leg 136, Site 834B scattered measurements on a few legs Leg 116-Bengal fan, intraplate compression

Thematic problems	Legs addressing those problems (**successful legs devoted to principal lithosphere objectives;** *legs partially successful or making secondary contributions to lithosphere objectives;* [minor contributions to lithosphere objectives]	Specific Goals of Long Range Plan or *Drilling Strategy* (2)--# of legs suggested for goal	Legs Addressing Strategies or Goals *Important Technical Advances*
Convergent margins			
Mass balance across subduction subduction zone	*Leg 110-Barbados with offshore section* *Leg 131 Nankai-offshore section* *Leg 129-Site 801C old crust composition*	Back-arc basin drilling (1) 1 case study of accretionary prism by 1993 (3)	Legs 127, 128 Japan Sea, Leg 135 Lau Basin Leg 110 Barbados, Leg 131 Nankai, Leg 146 Cascadia
Initiation and temporal variation in backarcs	[Leg 107 Tyhrrenian Sea-basalt and peridotite] *Legs 127/128 Japan Sea* **Leg 135 Lau Basin** [Leg 124 Sulu Sea] **Leg 126-Bonins, Sumisu Rift**	forearc diapirism by 1993 (1) by 1997 chemical composition of downgoing slab and sediments (3)	Leg 125-Mariana forearc
Temporal variation in arc and forearc volcanism and magmatic and tectonic links between backarc, forearc, and arc	**Leg 125-Mariana-Bonin forearc volcanism** **Leg 126-Bonin arc and forearc transect** *Leg 134-Vanuatu, effects of arc reversal* **Leg 135-Lau Basin forearc, Site 841**	*transects of forearc prisms including offshore reference holes* *transects of backarc, arc, and forearc with offshore reference holes*	Leg 110 Barbados, Leg 131 Nankai *Leg 125/126 Mariana-Bonin trnasects* *Leg 135 Lau Basin/forearc transects* (no offshore sites in either)
Fluid flow and pathways in accretionary and non-accretionary margins	**Leg 110-Barbados accretionary prism** **Leg 131-Nankai accretionary prism** *Leg 125-forearc serpentine diapirs* **Leg 146-Cascadia margin and CORKs**		
Ridge-trench collisions	[Leg 134-Vanuatu, fracture zone collision] **Leg 141-Chile Triple Junction**	by 1993 study ridge-trench collision and ophiolite obduction (2)	Leg 141 Chile triple junction
Mechanisms of subduction initiation and the nature of initial arc volcanism; origin of "supra-subduction zone" ophiolites	**Leg 125-Mariana-Bonin forearc volcanism** **Leg 126-Bonin arc and forearc transect** *Leg 134-Vanuatu, effects of arc reversal* **Leg 135-Lau Basin forearc, Site 841**		

[1] in one form or another the highest priority on most rankings of lithospheric objectives or questions

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Ocean History Panel White Paper

Executive Summary

The Ocean History Panel outlines four global experiments that examine the forcing and response of global environmental change, with recommendations for implementation for the near term (1994-1998) and medium term (1999-2003) of ODP and for a New Era of Ocean Drilling (post-2003). These experiments, which evolve from and update COSOD II (Conference on Scientific Ocean Drilling) themes, seek to understand the variations of the global environmental system as recorded in marine sediments with regard to: (1) orbital forcing, (2) rapid climatic change and internal feedbacks, (3) long-term changes and abrupt events, and (4) global sea-level change. These experiments require geographically distributed sites in arrays of latitudinal and bathymetric transects. Complete, continuous, and undisturbed recovery of all sediment lithologies is of highest priority. These efforts require continued access to a multi-purpose drilling vessel capable of sampling over a wide range of water depths and a wide range of sediment depths. Alternate platforms for drilling in very shallow waters will become increasingly important. In the near- and medium-term, we anticipate advances in drilling technology to improve core recovery, especially in difficult lithologies. Construction of complete sections from multiple holes at given sites depends on the continued development and application of non-destructive shipboard measurement techniques, down-hole logging tools, and software and data handling capabilities. In the long term, a change to larger diameter cores could address increased sediment sampling demands. Improved wireline heave compensation, more frequent acquisition of logging data, and narrower data smoothing windows are requirements for ultra-high-resolution logging. All of these efforts require high-quality site survey data as an integral part of designing drilling efforts, with particularly stringent site survey requirements for hazards evaluation for shallow water drilling.

I. Introduction

The mission of the JOIDES Ocean History Panel (OHP) is to: (1) to identify, evaluate, and prioritize scientific questions about the ocean's history and its role in global environmental change as recorded in marine sediments, and (2) to recommend an integrated program of drilling, logging, and sampling that will contribute to answering high-priority questions about the role of the ocean in global change. Aspects of the ocean environment of strong interest to OHP include the evolution of ocean climate, circulation, and chemistry; the evolution of the biosphere; changes in marine-terrestrial linkages through time; and global sea-level change. In this context, OHP seeks to understand the response of the ocean to major forcing functions of global environmental change. These forcing mechanisms define the temporal resolution needed to observe the variability of the system and the spatial and water depth arrays needed to constrain geographic changes in the system. Our central hypothesis is that temporal and geographic patterns of oceanographic change both respond to and control major aspects of the Earth's environment.

Previous strategic plans for studies of ocean history, resulting from COSOD II (Imbrie et al., *Scientific Goals of an Ocean Drilling Program Designed to Investigate Changes in the Global Environment*, Report of the Second Conference on Scientific Ocean Drilling (COSOD II), ESF, Strasbourg, France, pp. 15-46, 1987), the *Sediments and Ocean History Panel White Paper* (*JOIDES Journal* 15(1):40-58, 1989), and the *ODP Long Range Plan* (Ocean Drilling Program, *Long Range Plan*, 1989-2002, JOI, Inc., 1990, 119 pp.) were developed under four temporal and process-oriented themes: Neogene paleoceanography, pre-Neogene paleoceanography, carbon cycle and productivity, and sea level. Based on progress on these themes, we define here a new integrated experimental strategy that logically evolves from and updates these earlier statements of community vision.

We seek to understand the behavior of the global environmental system as recorded in marine sediments with regard to: (1) orbital forcing, (2) rapid climatic change and internal feedbacks, (3) long-term changes and abrupt events, and (4) global sea-level change. In the following, we first outline our experimental view of the global environmental system. Then, for each experiment, we describe the scientific justification, the objectives, the state of the art based on prior drilling, and an implementation strategy for the near term (1994-1998) and medium term (1999-2003) of ODP and for a New Era of Ocean Drilling (post-2003). Following this, we summarize the common priorities and outline the evolution of technology needed to accomplish our long-range vision.

II. A Global System View

In the context of OHP interests, the global environmental system is considered to include the entire hydrosphere, the atmosphere, the cryosphere, the biosphere, and the geosphere. Given information about the forcing of the climate system and its response from the oceanographic record, drilling strategies can be developed "to identify and understand the coupled physical, chemical and biological mechanisms that are the immediate causes of each observed change in climate" (COSOD II, 1987). To decipher the mechanisms of environmental change, we must first consider the nature of these forcing and response functions.

The ocean-climate system is a complex mixture of forcing on many time-scales and responses of many types and rates. External forcing includes: (1) periodic functions such as orbitally-induced changes in the distribution of solar radiation, (2) long-term tectonic and volcanic processes such as changes in the shape of continents and ocean basins, the orography of continents, and large scale volcanism, and (3) abrupt events such as the opening of critical circulation gateways and meteorite impacts. Some of the largest and most interesting climate responses result from internal feedbacks within the global environmental system from the effect of one climate component acting on another, even though the internal forcing may itself be a direct or indirect response to external forcing.

How do these concepts apply to the design of ocean drilling strategies to understand the causes and consequences of environmental change in Earth history? Operationally, they separate the paleoenvironmental record by time frame, establishing requirements for the drilling strategies and sampling resolution necessary for each experiment. Long-term changes affect the ocean-climate state and its evolution on scales of millions to hundreds of millions of years with abrupt events affecting the system on millennial to perhaps decadal scales. Superimposed on and interacting with this changing system are orbital-scale changes characterized by periodic fluctuations of tens to hundreds of thousands of years. Internal feedbacks occur on all time frames, but can be isolated at shorter periods where they may induce climatic oscillations of thousands to tens of thousands of years in the absence of obvious external forcing. Global sea-level change integrates processes on all time scales and thus merits particular attention with its own sampling strategy.

In all of these categories, our experimental goal is to assess the sensitivity and response of the ocean-climate system, and to "formulate and test quantitative models of the mechanisms of climate change" (Imbrie et al., ibid., p. 15). Our focus on forcing functions and responses forms the experimental framework for constructing drilling strategies to understand changes in the Earth's environment. A well-posed series of experiments targets specific components of the ocean-climate system on a variety of timescales. Below, we describe the drilling strategies for our four experimental themes: (1) orbital forcing, (2) rapid climatic change and internal feedbacks, (3) long-term changes and abrupt events, and (4) global sea-level change.

III. Evolution and Sensitivity of Global Environments: Forcing and Response Experiments

OHP Experiment 1: Orbital Forcing

Scientific Justification

ODP-based records of climatic, geochemical, biotic, and sedimentological changes in past oceans provide compelling evidence that the Earth's ocean-climate system has varied in response to changes in orbital geometry (the Milankovitch effect) over all time intervals from Holocene to Cretaceous. The Earth's orbital parameters, which affect the distribution of solar energy with season and latitude, change systematically with periods of 23 thousand years (Ka), 41 Ka, 100 Ka, 400 Ka, and 2 million years (Ma). This clearly defined temporal and spatial forcing provides a framework for testing hypotheses concerning the natural causes of environmental change. Examples of such hypotheses include:

1. What are the mechanisms, feedbacks, and sensitivity of the ocean-climate system response to known changes in solar radiation forcing?
2. Does rhythmic external forcing induce unidirectional changes in the dominant ocean-climate system?

Investigation of these questions will lead to greater understanding of the mechanisms by which orbital parameters influence the ocean-climate system; of the sensitivity of various processes and geographic areas to orbital forcing; of the role of forcing, direct and indirect, vs. internal feedbacks in global environmental change; and of the dynamics of potential threshold responses in the ocean-climate system. Understanding the history, processes, and dynamics of the ocean-climate system has direct relevance to questions of past, current, and future global change.

Objectives

Changes in Earth's orbit that cause variations in the distribution of solar radiation with season and latitude are known in detail for the past 10 Ma and in general for much longer time spans. Our objective is to measure the response of the ocean-climate system, including ocean circulation, ocean chemistry, and the ocean biosphere, to this known external forcing. The comparison of known forcing and measured response will allow us to identify aspects of the global system with linear and nonlinear responses and those with poorly-understood internal feedbacks (including atmospheric carbon dioxide levels) and perhaps internal oscillations. Understanding both externally and internally forced responses is necessary to constrain the mechanisms and sensitivity of environmental change.

The periodicities of orbital forcing define the temporal resolution needed to characterize the ocean-climate response to this forcing. For example, sampling intervals of about 4 thousand years (i.e., sampling every 8 cm in sediments accumulating at 20 m/Ma) are needed to resolve the ocean responses related to precession of the equinoxes with 19 Ka and 23 Ka rhythms. The latitudinal variability in these forcing functions and the strong horizontal and vertical gradients in ocean properties define the geographic and bathymetric resolution needed. Arrays of drill sites must have sufficient spatial and vertical resolution to identify key water masses; document circulation patterns; and define biotic, thermal, and chemical gradients. Experiments designed to test forcing-response hypotheses thus require complete and continuous recovery of all lithologies and the ability to accurately correlate sediment sequences within and between geographically separated sites, with biostratigraphy and magnetostratigraphy as fundamental tools for defining the chronologic framework. Other means for correlation include oxygen isotope stratigraphy, down-hole logging, and non-intrusive techniques for measuring sediment properties such as GRAPE (Gamma Ray Attenuation Porosity Evaluator) density measurements, magnetic susceptibility measurements, video imaging, and reflectance spectroscopy.

This experimental strategy requires the generation and analysis of high-resolution data documenting the ocean's response to orbital forcing under different Earth surface conditions. These differences include such factors as the presence or absence of major polar ice sheets, the concentration of atmospheric carbon dioxide, the pattern of deep ocean circulation and chemistry, and changes in continental location and elevation. The orbital experiment thus needs to be carried out throughout the geologic record in ocean sediments to isolate the role of each boundary condition. Because core recovery, stratigraphy, and chronology are best in younger sediments, many of these tests will be carried out in Neogene sediments. Examination of sensitivity to boundary conditions, however, dictates orbital experiments in Paleogene and Cretaceous sediments as well where key boundary conditions were radically different. OHP promotes the integration of these investigations of paleoceanographic history with numerical simulations of past conditions to evaluate quantitatively the sensitivity, variability, and evolution of global change processes.

State of the Art

As a result of ODP drilling, we have significantly extended our understanding of orbital signals in the Neogene. Using these signals as a pacemaker has resulted in an orbitally-tuned timescale back to the Miocene/Pliocene boundary, and, with continued work, this timescale will likely extend into the Miocene and earlier. Orbitally-tuned timescales are possible because of the development of non-intrusive techniques for measuring sediment properties shipboard and of software that permits construction in the drilling time frame of complete and continuous composite depth sections from multiple APC/XCB holes at given sites. The recognition of orbital cycles in deep-sea sequences has resulted in time resolution for pre-Pleistocene sediments that was never thought possible. These orbital timescales have provided a chronologic framework that can be used to accurately and precisely define rates of geologic and evolutionary processes.

We now know that orbital-scale cycles are pervasive in their effects on the sedimentary record. The amplitude and timing of the cycles vary spatially within the oceans as they evolve through time. As the patterns of orbital response emerge with increasing spatial and temporal resolution, they will provide major constraints on mechanisms of climate change.

Although ODP is working toward a first APC sampling of many Neogene environments by 1998, the sample arrays needed for the orbital response experiments will not be complete. In addition to recovering continuous (triple cored) sections from key spatial and water depth transects, existing materials have already raised additional questions that require denser geographic coverage in more focused experiments. Documenting and explaining timing relationships (lead, lag, or in-phase) among oceanographic responses from different regions represents one of the main opportunities for understanding the system's response to orbital forcing. Information on the timing of ocean responses will show how they are propagated throughout the ocean-climate system. Presently, only a few sites have long records that have been precisely tuned to orbital rhythms. This research strategy requires a global distribution of high-resolution sites spanning a broad range of latitudes and the full water column to monitor surface, intermediate, deep, and bottom water masses in all ocean basins.

Near-Term Implementation (1994-1998)

For the purposes of this experiment, OHP expects that the following field programs may be completed between 1994 and 1998:

1. Drilling a high-resolution depth transect in the western equatorial Atlantic to address climatic and oceanographic variations in this critical area of cross-equatorial transport of surface and deep waters and to examine the climatic history of South America (ODP Leg 154).
2. Drilling in the Mediterranean to understand the origin, significance, and geochemistry of Plio-Pleistocene sapropels and to address questions about the influence of rhythmic Late Cenozoic global circulation and climate changes on organic carbon deposition (scheduled Mediterranean drilling, 1995).
3. Drilling to refine the role of orbital forcing in the climate evolution of high-latitude and polar oceans, focusing on the second leg to address the Neogene history of the Arctic and high-latitude North Atlantic, a region important in

intermediate and deep water formation and a possible trigger for global climate changes (scheduled North Atlantic and Arctic Gateways [NAAG] II drilling, 1995). In addition, proposed drilling in the Caribbean will complement these efforts by helping to constrain Neogene history of mid-depth waters of the North Atlantic.

4. Drilling in climatically-sensitive upwelling areas to monitor global change, to establish marine-terrestrial linkages, and to estimate the contributions of upwelling productivity to geochemical budgets. Drilling in the near future will focus on the Cariaco Trench, the California Margin, and the Benguela Current/Namibia upwelling systems to recover long histories from these high-sedimentation-rate areas. Studies will concentrate on the evolution of these upwelling systems, their response to orbitally-induced, high-latitude cooling and changing wind systems, and their changing role in long-term carbon storage. The high sedimentation rates and laminated sediments in some locations will give ultra-high-resolution records for the late Neogene as well.
5. Drilling to assess southern hemisphere climates, patterns of global deep water circulation, and biosphere changes in the South Atlantic and in the South Pacific.
6. Drilling a high-resolution bathymetric transect in carbonate sediments in the sub-Antarctic Atlantic sector to fill gaps in Southern Ocean history revealed by previous drilling. High-resolution records of such factors as productivity, temperature, sea ice coverage, etc., are crucial for understanding global climatic variations in short- and long-time frames, including feedback mechanisms.

Medium-Term Implementation (1999-2003)

In addition to completing and expanding the coverage of critical open-ocean depth and meridional transects as described above, medium-term drilling objectives will likely focus on marine-terrestrial connections and on further efforts in high-latitude oceans. Marine records offer the possibility of defining the linkages and feedbacks between terrestrial and marine environments by direct correlation. Although marine records provide continuity and time scale advantages over terrestrial sequences, the records of faunal and floral changes derived from terrestrial sources provide direct evidence of the terrestrial paleoenvironment. Strategic initiatives could include correlation of East African and northwest Indian Ocean sequences using Plio-Pleistocene tephra layers, recovery of Bengal Fan sediment sequences to understand the temporal evolution of Himalayan uplift and weathering, and comparison of nearby lacustrine and marine sediment records in western North America.

High latitude and polar oceans are key components of the global climate system that strongly influence terrestrial climate and control the formation of intermediate, deep, and bottom waters. General paleoceanographic and climatic history of southern high-latitude areas was deciphered by ODP legs to the Atlantic and the Indian Ocean sectors of the Southern Ocean. Recently, the first of two legs concerned with North Atlantic and Arctic Gateways was completed, and a second leg is scheduled. The recent results obtained from continental ice cores drilled on Greenland and Antarctica emphasize the need to improve high-resolution marine records (at Milankovitch to sub-Milankovitch time scales) in both northern and southern polar oceans. Experiments should address the spatial patterns of glacial inception; direct forcing of surface water changes; the development of zonal bands and frontal systems; changes in sea ice distribution; changes in paleoproductivity; and the history of cold bottom water and intermediate water mass formation.

Potential drilling programs in these areas, in addition to the bathymetric transect in the sub-Antarctic Atlantic sector given under near-term objectives, could include a bathymetric transect in the western North Atlantic to give open ocean sites with resolution comparable to that of ice core records for addressing the changes in circulation and heat and carbon budgets on these time scales; high-resolution Neogene drilling in the eastern equatorial Atlantic to address cross-equatorial heat transport, productivity, and the history of intermediate and deep water circulation; and programs to focus on the deep and intermediate water history in the southeast Pacific; the role of the Bering Sea in climate change; and North Atlantic variations in proximity to the Laurentide Ice sheet.

Comparison of Quaternary and Neogene responses at high resolution is a critical part of the strategy for understanding the sensitivity of the ocean-climate system. The extension of the orbitally-tuned timescales to older ages, perhaps aided by emerging logging technologies as well, has the best potential for determining the high-resolution age models needed to make meaningful estimates of the rates and fluxes of climate-sensitive sediment components. By 2003 we expect to see the beginning of orbital experiments in older (Paleogene and Cretaceous) sediments when important boundary conditions were different, based on progress on lower-resolution studies of these materials.

New Era of Scientific Ocean Drilling (Post-2003)

As we look forward to a new era of ocean drilling with enhanced capabilities, the role of orbital forcing of the oceans and the global environment will remain a first-order priority. We envision that enhanced coring/recovery capabilities will enable OHP to address questions of orbital forcing in more dynamic and high risk environments such as high accumulation-rate continental margin, shallow water, and polar ocean sites. We expect the need for geographically-distributed sites to continue.

A high priority will be to improve recovery to obtain continuous, complete, and high-quality older

Neogene, Paleogene, and Cretaceous sediments so that orbital-scale variations in biotic, chemical, and sediment components can be quantified under different boundary conditions. These different Earth modes will test the response models developed in the more recent geologic record; this will provide important insights about the sensitivity of the ocean to orbital forcing.

OHP Experiment 2: Rapid Climatic Change And Internal Feedbacks

Scientific Justification

Analyses of ice cores and high accumulation rate oceanic sediments demonstrate that rapid environmental changes, on time frames from a few years to millennial scale, are common in Earth's recent history. These rapid changes, in the absence of obvious external forcing, pose critical questions:

1. Is Earth's environmental system inherently stable or unstable?
2. Does the ocean-climate system return to its previous state after a perturbation ends or is a new state established?
3. Do feedbacks in the Earth-atmosphere-ocean-ice-biosphere system produce predictable oscillations or are some aspects of global environmental change unpredictable?

These questions are immediately relevant to society as humanity's unintended experiment in global environmental change proceeds. Answers on relevant time scales may come from oceanic sediments accumulating at very high rates, such as on continental margins; in enclosed basins; and in sediment drifts. Laminated sediments from anoxic basins can also address interannual to decadal variability and provide the means to extend instrumental observations.

Objectives

Determining mechanisms that drive short-term environmental excursions, such as sudden steps in climate from one equilibrium state to another or sudden changes in the frequency and/or amplitude of variability, requires that we consider Earth's climate, chemistry, and biota as a linked system. The central goals are to determine the sensitivity of each component and the coupled system to change and to identify the internal feedback mechanisms that drive change. Critical factors to be constrained are ice in the sea and on the continents, sea level, latitudinal and bathymetric temperature gradients, oceanic transports of heat, salt, and nutrients and variations in biological productivity, in atmospheric greenhouse gases, in winds, and in net fresh water fluxes. External forcing such as large volcanic events or solar variability must also be considered. Only by using a combination of geologic, biotic, and chemical proxies of these oceanographic, biotic, and climatic components at high temporal resolution will it be possible to document the responses of the ocean-climate system on a human timescale. The use of these data with dynamic Earth system models to test hypotheses will lead to quantitative characterization of feedback mechanisms.

This experiment will require documentation of stable ocean-climate states and of regional and global rapid climate changes and determination of critical threshold levels for initiation of feedbacks leading to regional and/or global climate changes. An operational goal is thus to obtain appropriate records to study the long-term evolution of rapid climate and environmental variability under different climatic boundary conditions. Conventional piston coring can only provide short records in ultra-high sedimentation rate areas. Longer records must be recovered by scientific drilling.

State of the Art

Dramatic changes in the ocean have recently been found in North Atlantic sediments, especially during the last glacial cycle. These changes, referred to as "Heinrich Events," suggest massive changes in both upper-ocean and deep-sea environments, as well as in atmospheric circulation and chemistry, with potentially global consequences. Their cause is as yet uncertain, and their temporal and spatial distributions, and those of other rapid changes, are not well-defined. Ultimately, whether these rapid ocean-climate changes are global or regional, whether they occur at all times or only in certain climatic states, if they are unique or if they are among a large array of rapid climatic phenomena remains unclear. Aspects of the current hypotheses, especially the role and response of the ocean in these rapid changes, and the global implications of these processes need to be evaluated. This highlights the importance of obtaining marine sedimentary records with a resolution comparable to that of ice core records.

Near-term Implementation (1994-1998)

Some potential targets for the next four years include high-latitude North Atlantic sediment drifts (as part of NAAG II), the Blake-Bahama Outer Ridge, the Bermuda Rise, the Southern Oceans, and selected basins on continental margins such as the Cariaco Trench, the California Borderland basins, and along the southwest African margin. Because suitable drilling targets do not exist everywhere, recovery of these types of records does not always requires a full drilling leg. Incorporating this type of site into geographically appropriate (but not necessarily thematically-related) drilling programs requires scheduling flexibility and foresight.

Medium-term Implementation (1999-2003)

We expect additional high-quality sites to be identified that will help define the global distribution of rapid climatic events. We anticipate the development of new geochemical and biotic proxies for use with small samples and continuing application, including increasing automation, of existing proxies to better characterize environmental changes at high temporal resolution.

New Era of Scientific Ocean Drilling (Post-2003)

Predicting the long-term development of a field that is just now being defined must be very general. We see the need to study rapid environmental changes under climatic boundary conditions warmer than those of today or of the late Pleistocene ice ages as tests of possible future scenarios for Earth's climate system. Scientific questions arising from previous work, along with technological advances, may dictate the return to previously drilled sites to improve or extend records. Advances in drilling techniques should broaden the range of environments sampled, including the potential for recovering long records from corals which would yield information on seasonal-to-interannual climate variations.

OHP Experiment 3: Long-Term Changes And Abrupt Events

Scientific Justification

Over much of the past 120 Ma, Earth's climate has been warmer than at present, especially at high latitudes, and the ocean-climate system must have operated quite differently. Ocean chemistry and ocean circulation have changed through time. Marine productivity, in intensity and geographic distribution, has changed, influencing the resulting composition of the sedimentary record (e.g., opaline silica, calcium carbonate, organic matter). Abrupt changes in the global environment are also clearly documented. Long-term and abrupt external forcing (in addition to external forcing by orbital cycles) must play a major role in influencing the ocean-climate system. These forcing functions include tectonic processes such as changing continental geography and mountain uplift (influencing ocean and atmosphere circulation and composition and continental weathering), volcanic processes (resulting in long-term and abrupt changes in the concentrations of atmospheric greenhouse gases and aerosols), and extraterrestrial processes such as meteorite impacts. The critical questions include:

1. Does the ocean-climate system respond only gradually to gradual forcing or are threshold effects important?
2. How do changes in continental geography and mountain building influence the ocean-climate system, including chemical and physical weathering of continents?
3. Were Cretaceous and early Cenozoic episodes of moderate to extreme global warmth the result of changes in atmospheric composition or of changes in global oceanic and atmospheric heat transport?
4. What are the nature of the onset and the degree of stability of Antarctic ice sheets?
5. What is the role of different modes of deep water formation in episodes of warm climates and in biogeochemical cycles?
6. How do catastrophic events such as meteorite impacts or massive volcanic events influence the global environmental system?
7. How rapidly does the biosphere respond to abrupt climatic and/or oceanographic change and with what types of responses (e.g., evolutionary change, productivity, community structure, biogeography)?

Our understanding of the global ocean-climate system requires a thorough evaluation of the effect of different boundary conditions and of catastrophic changes on the system's operation. Ocean drilling can provide the material needed to define the scale of these past changes in the ocean-climate system, to determine the role of greenhouse gases in long- and short-term changes in the ocean-climate system, and to characterize the biosphere's response to climate change on both regional and global scales. To this end, we encourage the combination of synoptic reconstructions of global climate and ocean circulation and chemistry resulting from this experiment with a strategy of numerical modeling. This integration of measurements and predictive modeling serves to evaluate model assumptions and to guide sampling efforts to critical regions, with both aspects relevant to understanding future environmental change.

Objectives

To better understand the operation of the ocean-climate system in radically different states, we must develop synoptic reconstructions of critical time intervals. These reconstructions should consist of quantitative estimates of both boundary conditions and oceanic responses on a global scale, including the planetary temperature gradient, ocean chemistry and sedimentary fluxes, and the modes of ocean and atmospheric circulation. The rates of change must be well defined, especially in the cases of relatively abrupt shifts in climate.

To accomplish these objectives we must obtain geographic arrays of continuous, long time series in ancient sedimentary sequences with well-defined orbital cycles to constrain sedimentation rates. Defining the rate of taxonomic evolution (i.e., the number of evolutionary entries and exits per unit time) is important for biostratigraphic and biochronologic resolution. Highest turnover rates for carbonate-producing plankton are consistently found in the tropics. The recovery of continuous low-latitude Paleogene and Cretaceous sections is essential for determining the rates of taxonomic evolution and the limits of biostratigraphic resolution of the carbonate producing plankton. Both high and low latitudes need to be sampled for determining the corresponding rates and geographic limits through time for silica producing plankton. We must apply proxies to precisely define past changes in the concentration of key greenhouse gases. Some progress has been made in this area, but more reliable data are needed, particularly for the episodes of extreme global warmth. We must identify and constrain other major processes involved in the carbon cycle that may act to either dampen or enhance changes in atmospheric carbon dioxide. This includes, on long-time scales, the weathering and burial of carbonate and organic-carbon rich rocks, and, on short time scales, ocean-atmosphere circulation and marine productivity.

We suggest concentration on intervals of time when the ocean-climate system was radically different from the present or when the ocean-climate system was changing abruptly. Examples of different states include warm episodes in the mid-Pliocene, early Eocene; and mid-Cretaceous and glacial intervals in the early and middle Oligocene and Pleistocene. Examples of abrupt shifts in climate include global warming in the latest Cenomanian-earliest Turonian and in the latest Paleocene; expansion of ice-sheets on Antarctica in the earliest Oligocene; and the inception of the Pliocene/Pleistocene glacial intervals. In addition, discrete anomalous events such as the changes at the Cretaceous/Tertiary boundary are relevant to this experiment.

State of the Art

Ocean drilling has contributed significantly to defining the character and timing of long-term and abrupt changes in the global environment. Drilling has demonstrated that large ice-sheets probably first appeared on Antarctica in the earliest Oligocene and have remained ever since. In the past, different regions of the ocean (e.g., the North Pacific, subtropical marginal basins) may have been major sources of deep water. In the time prior to the Oligocene and extending back to at least 120 Ma, the oceans were relatively warm and dominated by lengthy episodes of moderate to extreme warmth at high latitudes. Discrepancies exist in the tropical surface temperatures estimated based on geochemical proxies (oxygen isotopes) and biotic evidence (paleobiogeography) from sediment samples compared to climate model estimates. The transitions between warm and cold climates were not always gradual, as might be expected from gradual changes in external forcing, but sometimes occurred abruptly. The recognition of these abrupt shifts and associated transitional climates has given rise to theories on climatic thresholds and feedbacks capable of accelerating and/or amplifying climatic transitions. Identification and quantification of mechanisms that maintain climatic stability and of feedback processes that induce abrupt change under radically different climatic states is central to the mission of OHP.

We now have the background to design focused drilling experiments regarding the factors that drive long-term changes in global environment. More accurate reconstructions of the evolution of the Antarctic cryosphere and the growth and stability of ice sheets (temperate vs. polar character) should help resolve existing discrepancies between land-based and marine-based records. We have demonstrated that reconstructing Antarctic glacial history requires coring not just on the margins where sequences tend difficult to date and incomplete due to erosion, but on nearby submarine highs too distant to be eroded by ice sheets, yet near enough to receive ice-rafted sediments from icebergs produced by those ice sheets. Combined investigation of latitudinal isotopic gradients with analyses of the biogeographic distribution and abundance pattern of microfossil assemblages will aid in this effort as well. The recognition of well-defined orbital cycles in pre-Neogene sediments allows the reconstruction of high-resolution records of ocean-climate history for the Paleogene and Late Cretaceous. Latitudinal transects are critical in this effort. By drilling depth transects in key locations, vertical and horizontal water mass distributions can be determined, a strategy that has worked well for the Neogene. Extension of this strategy into the Cretaceous will provide critical insight into alternative modes of ocean circulation.

Near-Term Implementation (1994-1998)

The next several years of planned ocean drilling will document only a few aspects of long-term ocean history needed to evaluate the role of tectonism and volcanism in climate change and to better define how the ocean-climate system responds in warmer climate states. Some drilling will focus on obtaining sediments needed for reconstructing changes in tropical climates. This includes drilling in the western equatorial Atlantic (Ceara Rise, ODP Leg 154) and potential drilling back to 90 Ma in the Caribbean. These studies are critical since current climate theory suggests that with future increases in greenhouse gas levels, the high latitudes will undergo extreme warming while the tropics remain more or less stable.

Medium-Term Implementation (1999-2003)

Drilling efforts should focus on obtaining globally-distributed bathymetric and latitudinal transects necessary for defining Neogene and pre-Neogene changes in the low and high latitudes. For example, the sedimentary record of the Pacific basin, because of its immense size and its importance in ocean circulation and chemistry, must be well understood to fully characterize changes in the ocean-climate system. Bathymetric and latitudinal transects in the South Atlantic are also of strong OHP interest. High-priority objectives for these sedimentary records include reconstructing past changes in ocean and atmospheric carbon dioxide levels and developing a high-resolution astronomical time scale throughout the Cenozoic for the purpose of better constraining rates of change. During previous drilling, very little well-preserved, unlithified sediment suitable for building climatic, geochemical, and paleontological reconstructions of the Cretaceous and early Eocene greenhouse worlds was collected from the Pacific Ocean. This was due primarily to the fact that much of drilling focused on obtaining high-resolution Neogene sequences, and it was unclear where well-preserved Paleogene and Cretaceous material could be recovered.

A program of drilling is required that specifically targets Paleogene and Late Cretaceous sediments. The key to success for pre-Neogene depth transects is site survey information defining the paleo-water depth of the sites and indicating how much sediment of the targeted age is present. Drilling efforts should be concentrated on obtaining sequences from: (1) the equatorial and low-latitude Pacific, (2) the South Atlantic, (3) the high-latitude Bering Sea, (4) the Pacific sector of the Southern Oceans, particularly the southwestern Pacific east of New Zealand, a critical gateway region for deep ocean circulation, and (5) other ocean regions as appropriate. Low-latitude drilling should build a north-to-south transect across the equator between 30°N and 30°S paleolatitudes. Where possible, a drilling strategy should be employed that involves using previously-drilled holes and high-resolution seismic stratigraphy to identify regions where Paleogene and Cretaceous sediments outcrop or have a relatively thin Neogene overburden to minimize problems of sediment diagenesis. We require either a means of penetrating cherts without compromising recovery of sediments or the application of a strategy using high-resolution seismic stratigraphy to locate gaps in chert layers.

New Era of Scientific Ocean Drilling (Post-2003)

The new era of drilling will be ready to address more focused questions of long-term global change. Several problems must be addressed, including: (1) establishing the existence and importance of alternative modes of ocean circulation, (2) locating the major sources of bottom waters in different time intervals, and (3) defining the short- and long-term glacial history of Antarctica.

The first two problems must be addressed by building three-dimensional reconstructions of deep water circulation and chemistry. This will require vertical depth transects in key locations in the world oceans. To date only one vertical depth transect with complete recovery for more than two sites has been drilled for the pre-Neogene (Leg 154, the Ceara Rise in the western equatorial Atlantic) and it only included the Oligocene. Other regions where similar depth transects are required include the northwest Pacific, the sub-Antarctic Indian Ocean on Kerguelen Plateau, the South Atlantic including the South Atlantic sector of the southern oceans on Maud Rise (where the first evidence of warm saline bottom waters was obtained, but where only two sites were drilled), and the North Atlantic ocean. Ideally, each of these depth transects must consist of sites throughout the full water column with a minimum of 500-1000 m resolution to adequately define water masses. The third problem will require additional drilling in the circum-Antarctic Southern Ocean. Previous drilling provided a tantalizing glimpse of this region's climatic sensitivity.

OHP Experiment 4: Global Sea-Level Change

Scientific Justification

Sea level has varied through geologic time, both in response to tectonically driven changes in the size of the ocean basins and to changes in the volume of ice stored on land as ice sheets. However, disagreement remains over how frequently sea level changes, particularly during times when no evidence exists for ice sheets on land, and also over the magnitude of the sea-level fluctuations that appear to be recorded in the depositional packages (sequences) that are commonly observed near the edges of the ocean basin and on oceanic islands.

Geologic records suggest that warm, equable climates are associated with times of high sea level. The amount of the Earth's surface covered by water has an effect on the amount of solar radiation absorbed, stored, and available for heating the atmosphere through the transfer of both sensible and latent heat. Many mathematical models of climate require a knowledge of the fractions of the Earth's surface as land and sea as a boundary condition. The flooding of continental platforms and the creation of broad shallow seas may therefore have a profound effect on: (1) atmospheric heating and surface ocean circulation, (2) the creation of high salinity waters that may drive deeper circulation, (3) the transport of sediments from the continents to the ocean basins, (4) the fractionation of carbonates between the deep and shallow seas, (5) the creation of strong oxygen minimum zones in shallow to intermediate waters, (6) the creation of organic rich deposits in these same shallow seas, and (7) the rate of continental weathering. In contrast, times of lower sea level appear to be associated with relatively cooler climates, different surface circulation patterns, perhaps more thermally-driven deep circulation, and higher accumulation rates of both terrigenous material and carbonates in the deeper ocean basins. Repeated changes in sea level may act as a "pumping mechanism" that first traps sediments on terrigenous continental margins during highstands, and then strips them off and carries them to the deep sea during lowstands.

In addition to its direct effect on the climate system, a changing sea level also has a profound influence on circulation within the ocean, on the chemical character of the ocean waters, and on the preserved sedimentary record. Understanding such aspects of sea-level change is central to OHP's goals and mission. Because sea level is a global integrator of climatic and tectonic processes, and because a drilling strategy to constrain its history, causes, and consequences is operationally distinct from other OHP efforts, it is classified as a separate experiment, compatible on all timescales with the other OHP experiments.

Objectives

Two primary questions that must be answered regarding sea-level change are:

1. Are the apparent rises and falls of sea level seen in near-shore deposits around the world synchronous (and therefore evidence for eustasy)?
2. What are the magnitudes of any such rises and falls?

Knowing the answer to these two questions will allow us to develop strategies for testing what mechanisms are likely controlling the observed character of these depositional packages and for evaluating the impact of sea-level change on climate, ocean chemistry, and ocean circulation. If, as proposed, short-term changes in sea level occur as globally synchronous phenomena, their causal mechanism(s) must affect the volume of water in the ocean basins, the size of the ocean basins, or the average base level of storm waves. Such changes would require either an unexpectedly quick tectonic change (basin size) or a significant climatic change (ocean water volume or wave energy). Knowing the true magnitudes and timing of apparent eustatic changes would provide powerful constraints on the mechanisms that could explain the existence of these changes and greatly increase our fundamental understanding of ocean history and climate change.

State of the Art

Work to date on such sequences suggests that fluctuations in sea level occur much more frequently, and on too short a time scale, to be explained by tectonic mechanisms for changing ocean basin volume. Other viable mechanisms for the creation of these depositional packages have been proposed (for example, current or climate control); however, the testing of such models of depositional control is still in its very early stages. To date, drilling near continental margins, together with the gradual development of detailed records of oxygen isotopes, have given us clear indications that both long-term and short-term changes in sea level have taken place. We have yet to link unequivocally the isotopic records from the deep sea and the stratigraphic records from the shallow water areas. The linkage of these records is critical to evaluating both the synchrony and magnitude of events. Plans are being made to complete the transect of the New Jersey margin and proposals have been submitted to drill additional near-shore areas in the Bahamas, Campeche Bank, the Great Australian Bight, and offshore Japan.

Planning drilling programs of near-shore areas are time consuming and expensive. They require extensive seismic survey and detailed interpretation of seismic reflection data; however, such surveys have been carried out in many areas by industry and government and are being made available for use in scientific drilling. The main difficulties lie in recovering the appropriate near-shore sections. Difficulties include such technical problems as drilling safety; shallow water drilling; core recovery; as well as geologic considerations, such as fossil preservation, erosional breaks, and diagenetic alteration of the sediments. Although tests of synchrony do not require the highest precision dating of all surfaces at all sites in the transect provided that the very shallow sites can be accurately tied to the higher-resolution basinal sites, precise timing of events is critical to OHP goals. Tests of the magnitude of sea-level fall do, however, require a very careful analysis of the proximal facies in the lowstand deposits. Here the development of better proxy indicators of paleo water depth could greatly aide our research efforts.

Near-term Implementation (1994-1998)

Testing the reality of events on the global sea-level scale requires information from all ocean basins and both hemispheres. And, because sea-level changes have their greatest direct effect on shelf sediments, testing the Sequence Stratigraphic Model requires drilling complete passive margin transects. OHP encourages the development of closely integrated sea-level proposals spanning both the process interests of the Sedimentary and Geochemical Processes Panel (SGPP) and the ocean history interests of OHP, perhaps via the mechanism of an informal dual panel advisory group. The overall history of sea-level fluctuations is so complex that no single technique, or single drilling leg, can be expected to provide a global picture of sea-level variations. Given the degree of cooperative planning called for by the Sea Level Working Group Report (see shortened version, *JOIDES Journal* 18(3):28-36, 1992), the amount of surveying required, the detailed interpretation of the survey data, and the global coverage needed to address the main objectives of this experiment, we should begin now to develop an array of potential transect locations.

Medium-term Implementation (1999-2003)

Considering the extent of the planning efforts required by drilling across the ocean margins and the logistical constraints in achieving global coverage, we are not likely to reach quickly the desired ends of this experiment. We presently have proposals for a return to the New Jersey margin and for further drilling on the Bahamas transect. We have at least two other proposals that address the sea-level experiment and are likely to achieve high ranking as they develop further. All of these proposals address specifically the sea-level changes during the Neogene, when variations in ice volume provide a very plausible mechanism for changing sea level. Priority depends on demonstrating that events can be dated well enough to evaluate their global significance. Based on the results from these drilling efforts we should extend the global coverage of our transects, and then use our experience with the Neogene to plan to extend our investigations back into the early Paleogene when ice volume may not have played a dominant role in the apparent fluctuations of sea level.

New Era of Scientific Ocean Drilling (Post-2003)

In this era we should have established a definitive Sequence Stratigraphic Model based on our drilling of Neogene margin sequences and the linking of these sequences to the oxygen isotope record. We should have a much greater appreciation of how sea-level changes affect deposition on the margins, of the magnitude and speed of these changes, and of their quantitative relationship to the Neogene oxygen isotope record. At the same time we should have extended our detailed oxygen isotope records through the Neogene and well into the Paleogene and Cretaceous. Based on this knowledge we should be ready to address that part of the experiment that investigates the application of the Sequence Stratigraphic Model to times when we believe continental ice volume could not have played a major role in sea-level change. Is this belief false? The few detailed Paleogene isotopic records available suggest that there were episodes when ice volume may have played a role in sea-level change. Yet at other times, when seismic records seem to indicate shifts in depositional packages that are attributed to significant changes in sea level, the oxygen isotopic signal does not seem to show a high degree of variation.

These older sequences will be more difficult to reach and recover; therefore, drilling efforts may take longer to complete. Safety hazards must be even more carefully evaluated, and additional shipboard safety procedures and equipment may be required. The result may be that fewer transects can be drilled. However it is hoped that given our experience with the Neogene transects, and with a more extended planning period to search for the best drilling locations, we can address the objectives of this experiment in a comparatively efficient and economical way.

IV. Common Priorities and Technological Needs

Several priorities are common to all four themes. These experiments require geographically-distributed sites in arrays of latitudinal and bathymetric transects, including sites in difficult drilling environments such as the Antarctic, the Arctic, and shallow water settings. Complete, continuous, and undisturbed recovery of all sediment lithologies, including sandy sediments, is of highest priority, with multiple holes required at given sites to facilitate the construction of complete sections and to supply sufficient material for high-resolution, multi-proxy analyses. These efforts require continued access to a multi-purpose drilling vessel capable of sampling over a wide range of water depths and a wide range of sediment depths. Alternate platforms for drilling in very shallow waters will become increasingly important.

The scientific requirements of these experiments also define common technological needs. In the near-term, we anticipate advances in drilling technology to improve core recovery, especially for lithologies such as gassy, organic-rich sediments that expand on retrieval; siliceous-rich sediments (e.g., the use of washover techniques to extend the depth of recovery of APC); and alternating hard and soft lithologies such as interbedded cherts and chalks. The construction of complete sections at each site will rely on the continued application and new development of non-intrusive shipboard measurement techniques and down-hole logging techniques and on improved software and data handling capabilities for core-to-core and core-to-log correlations.

In the medium term, the increasing development and application of multiple tracers at high resolution will continue to require multiple holes at given sites and precise correlations between holes and between different sites. Continued improvements in rapid, non-destructive sediment scanning techniques and in shipboard computing and data handling are required. Advances in drilling technology to improve recovery of lithologies such as shallow water carbonates, sands, and alternating hard and soft or coarse and fine lithologies are required. In the long term, a change to larger diameter cores could address increased sediment sampling demands, reducing—but not eliminating—the need for multiple holes at given sites. The application of multiple techniques to identical samples is key to achieving our scientific goals, as is the construction of complete sections. Improved wireline heave compensation, more frequent acquisition of logging data, and narrower data smoothing windows are requirements for ultra-high-resolution logging. Higher resolution logging would aid in resolving true depth frameworks in core-to-core and core-to-log integration efforts and in delineating sequence development and guiding detailed sampling efforts for sea-level experiments.

All of these efforts require high-quality site survey data as an integral part of designing drilling efforts. Mechanisms for funding site survey work are therefore of great concern. Exploratory drilling has been supported in the past by site survey data acquired over the past few decades, with this reservoir of information now running low. The more focused drilling characteristic of recent efforts and of the experiments described here requires improved site survey data including high-resolution digital seismics with high spatial resolution and better knowledge of bathymetry; short survey cores are required as well for preliminary characterization of sediments to be drilled. Shallow-water drilling efforts pose particularly stringent site survey requirements for hazards evaluation as well, and mechanisms for funding these need special attention.

SEDIMENTARY & GEOCHEMICAL PROCESSES PANEL WHITE PAPER

Overview

The Sedimentary and Geochemistry Processes Panel (SGPP) was established by the Planning Committee (PCOM) in 1989 with the mandate to develop, review and plan drilling programs that focus on the study of processes controlling sediment distribution and geochemical activity on and beneath the deep-ocean floor. SGPP identified five broad thematic areas that could be studied using the investigative potential of the *JOIDES Resolution*: (1) sea level and the record of eustatic change, (2) material cycling and sediment distribution processes, (3) fluid circulation through the crust and geochemical balances, (4) metallogenesis and its control by tectonics and host material and (5) fluctuations in paleocean chemistry and geochemical budgets. In addition to the recovery of material and fluids from the deep sea, SGPP's process-oriented drilling program promotes the utilization of bore holes as natural laboratories in which experiments can be conducted to understand the mechanisms of ongoing processes and develop actualistic models. During the last five years, great strides have been made towards the completion of certain SGPP thematic objectives, while lesser progress has been made in other areas. Some recent major thematic results include the demonstration that fluids moving through and flowing out of active margins and the crests and flanks of mid-ocean ridges are major contributors to the geochemical fluxes; the in situ study of active and fossil hydrothermal metalliferous deposits at ridge crests; and preliminary investigations of gas hydrate formation.

In light of recent results and with a concentration on what might be accomplished through ocean drilling by the end of the current program in the year 2003, SGPP now proposes to consolidate specific topics and focus future drilling efforts into the study of three thematic areas: (1) sea level and facies architecture, (2) fluid flow and geochemical fluxes and (3) carbon cycling from the seafloor to the base of the biosphere. Within the realm of the first two thematic areas, this consolidation permits the combining of previously overlapping objectives, such as sea level and sediments or fluids and metallogenesis, to achieve a more directed approach to understand specific global problems. The third thematic area proposes to link studies of the marine geosphere to processes that occur in the microbial biosphere beneath the seafloor from the sediment/water interface to the base of the biosphere, which SGPP defines as the depth where all microbial activity ceases.

These three thematic areas can be ultimately interlinked and related to important geologic problems, such as non-renewable economic resources, global climatic change, carbon cycling and microbial evolution. For example, sedimentary architecture, in response to sea-level changes, can determine the flow paths of fluids through a margin, as well as control the burial rate of organic carbon, whereas the microbial activity within the sedimentary column diagenetically alters porosity and permeability while influencing the preservation or destruction of the buried organic matter. In hydrothermal systems, the flow of fluids through the oceanic crust with its subsequent alteration releases dissolved components, which provide energy for microbial processes (chemosynthesis) and material for metalliferrous deposits at or just beneath the seafloor. The drilling program promoted by SGPP remains predominantly process oriented and proposals highly ranked by the panel reflect this orientation. In addition, proposals defining borehole experiments are encouraged.

Sea Level & Facies Architecture

Introduction

The Sea Level Working Group (SLWG) was commissioned by PCOM in 1991 to formulate a global ocean-drilling strategy for: (1) estimating the timing, magnitude and rate of eustatic changes as recorded in sediments and sedimentary rocks, (2) investigating the stratigraphic response to sea-level oscillations, and (3) determining mechanisms of eustatic change. The SLWG Report (1992) outlines a detailed, comprehensive drilling program to study sea-level processes that is contingent upon global coverage in a variety of tectonic, sedimentary, climatic and oceanographic environments. A primary SGPP goal within this program is to test models for eustatic sea-level change using sequence stratigraphy, and also to test sedimentary models for regional and relative sea-level changes. SGPP's interests are not in reconstructing a sea-level history but in understanding how sedimentary architecture is related to sea-level variations. These types of studies can provide an understanding of processes that will allow us to relate modern analogues to similar deposits that are widespread in sedimentary basins and hydrocarbon provinces, as well as to relate geophysical signatures to sedimentary architecture. The drill ship is well suited to this task because it provides continuous cores tied to a seismic-stratigraphic framework, allowing the integration of magneto-, bio-, and chemo-stratigraphies with seismic sequence analysis.

The integrated theme of sea-level and facies architecture represents a topic of extremely broad interest within the community of sedimentary geology. Initial focus on the Neogene marine record will allow sedimentologists to quantify the links among allocyclic forcing (e.g., eustacy and climate change), autocyclic processes (e.g., channel avulsion, migration of depositional lobes) and depositional products. The depositional products of interest should include siliciclastic shelf-slope successions, carbonate margins, submarine fans, and basins affected by local tectonic activity. Connections between process-and-product or cause-and-effect then can be applied to studies of all parts of the geologic record, including continental outcrops of all ages. This basic theme is very relevant to many earth scientists who normally work on land and frequently operate outside the framework of ODP. It also provides a link to other earth science initiatives, such as MARGINS, for which a drill ship will be an integral part of its science program to study continental margins.

Accomplishments to Date

Scientific advances have been made towards resolving certain aspects of the sea-level questions through the application of the three-pronged approach outlined by SLWG, using a combination of isotope stratigraphy, non-marine/marginal marine to "deep" basin transects, and atoll and guyot "dipsticks." Implementation of this global ocean-drilling strategy is, however, far from complete. In the shorter term, the sea-level program proposed by SGPP suggests that only drilling targets through Neogene sequences on both active and passive margins be pursued. The Neogene targets are best suited for sea-level investigations because they are accessible without deep drilling and the results can be used to achieve the following fundamental objectives:

1. To determine the effect of sea level on three-dimensional facies architecture
2. To evaluate the stratigraphic responses of continental margins to large amplitude Neogene sea-level changes
3. To identify and establish well-documented analogues for studies of sequence stratigraphic throughout the geologic record
4. To integrate borehole and seismic-reflection data, through multiple iteration, into predictive numerical models of margin evolution

SGPP considers that a primary responsibility of ODP in studies of sea level is to promote testing of the validity of "quantitative process models for sediment transport and distribution." Predictive models of stratigraphic responses to allocyclic forcing must be iterative. The accuracy of computer simulations will improve considerably as boundary conditions become increasingly realistic. This geologic realism is established most effectively through the observational framework of ODP drilling. At the same time, strategies for identifying both regional transect corridors and local site targets for additional drilling will become more refined if their locations are based on sophisticated predictive models. Thus, SGPP proposes to work toward a long-term goal of establishing representative end-member examples for sea-level transects, and ODP must be prepared to return to those sites for multiple phases of drilling.

To date, the following dedicated sea-level drill programs have been in part accomplished in SGPP's sea-level program to drill non-marine/marginal marine to "deep" basin Neogene transects:

1. Carbonate and mixed siliciclastic/carbonate environment: NE Australian Margin (Leg 133), Oligocene to Recent intermediate to deep water sites were drilled; Pleistocene shallow water sites on the Great Barrier Reef to complete the transect from the Australian shelf to the Queensland Plateau will be drilled in 1994/95. Sea-level related results from Leg 133 correlated Pleistocene oxygen isotope curves with sedimentary architecture and documented the effects of paleoclimatic versus sea-level fluctuations on carbonate development.
2. Siliciclastic environment: New Jersey Margin (Leg 150), Oligocene to Recent deep water sites linked by seismic profiles with continental drill sites; needs shallow and intermediate water sites to complete the transect.

Drilling on Amazon Fan during Leg 150 has demonstrated the potential to achieve high-resolution understanding of the rapid, punctuated growth of deep-sea fans, under the forcing of climate and sea level. This type of study aimed at understanding construction of major sediment packages at the continental margins, tied to known morphology, can serve as a model for future programs. Sediment characteristics (e.g., texture, structures, organic content) fit within a morphological and chronological framework can then be used to constrain quantitative models of sedimentary and geochemical processes in thick sediment piles. Another component of the three-pronged approach recommended by the SLWG, the "dipstick" drilling of atolls and guyots model, was tested during Legs 143 and 144 in the west central Pacific.

Technology requirements for SGPP's sea-level program include the need for alternate platforms to drill shallow-water sites, as well as the ability to drill intermediate-water sites on continental margins requiring site hazard surveys and possible modifications to the *JOIDES Resolution*. There is a critical need for development or adaptation of drilling tools that can achieve good recovery in friable shallow-water carbonates and unconsolidated sands.

SGPP 1996-1998 Drilling Program

SGPP plans to focus drilling efforts related to sea-level problems on the completion of selected non-marine/marginal marine to "deep" basin transects. During the 1996-1998 period, SGPP proposes that the intermediate-to-deeper water sites in the Bahamas Transect be drilled. The shallow-water, platform margin sites in this transect were previously drilled using a jack-up drill rig. The completed Bahamas Transect in a carbonate environment will provide a sea-level study complimentary to that on the siliciclastic New Jersey Margin, with both studies being in the same age sediments and from the same passive margin. Also, during the same period, SGPP proposes that the shallow-to-intermediate water sites on New Jersey Margin be drilled in order to complete this very important transect. This will require a special site hazard survey for the intermediate-water drilling and an alternate platform for the shallow-water sites. SGPP views the completion of the Bahamas and New Jersey Transects during the 1996-1998 period as essential components in a minimum sea-level program.

SGPP 1999-2003 Drilling Program

During the 1999-2003 period, in line with SGPP's interests in understanding how sedimentary architecture responds to sea-level variations and the recommendations of the SLWG, SGPP foresees the need to drill at least four more transects to establish global coverage in a variety of tectonic settings, in different latitudinal positions, with different sediment compositions and sources. SGPP proposes that drilling be scheduled on the following types of environments:

1. A small, sandy submarine fan within a continental borderland setting, such as on the California margin: To provide the closest analogue for most of the well-studied examples of turbidites in the continental stratigraphy. When compared to large muddy systems along mature passive margins, such as the Amazon Fan, the borderland fans represent the opposite end member of textural and physiographic possibilities. Some of the borderland fans, in addition, are sites of active sediment accumulation during highstands of sea-level. This is because associated submarine canyons are able to maintain their head positions near the highstand shoreline, where they can intercept sediment from littoral cells and funnel turbidity currents into deeper water. SGPP suggests, therefore, that the paradigm of linking sea-level lowstands to phases of intensified canyon activity and aggradation/ progradation of all types of turbidite-fan systems requires further scrutiny. One means of testing the linkage would be through direct comparison of facies architecture and depositional cyclicity for two nearby fans; one linked to the littoral zone during Holocene highstand conditions and the other detached from the inner shelf and mantled by a Holocene mud blanket. To achieve these goals, however, ODP must develop a reliable system for recovery of thick, uncemented sands.
2. Near an ice margin, such as in the Antarctic: To target at least one grounded-ice margin as part of the overall sea-level theme. This is important for several reasons. First, this strategy might help eliminate some of the discrepancies that exist between seismic-stratigraphic inferences of eustatic sea-level change and inferences of global ice volume derived from isotopic analyses. Second, well-designed high-latitude drilling transects would provide important constraints on both the timing and amplitude of ice-volume changes over periods of time that are much longer than the last two glacial cycles (i.e., back into and through the Neogene). This information would have obvious appeal to investigators of global climate change. Finally, the direct sedimentologic consequences of changing the grounded-ice volume are contained only in the prograded sediment wedges of high-latitude margins, such as Antarctica. Consequently, definitive links between three-dimensional facies architecture and fluctuations in grounded-ice volume can be established only through high-latitude drilling transects.
3. On a convergent margin, preferably within a forearc or foreland basin that displays the effects of a simple history of vertical tectonics: To test the effects of eustatic sea-level change on convergent margins. SGPP believes this should be stressed rather than ignored. Eustatic cycles certainly can be overwhelmed by tectonic controls on rates of sediment influx; however, this is not always the case. The challenge is to document how the combination of eustacy and tectonism leads to the development of a characteristic facies architecture. Facies patterns, in turn, exert a strong influence on the structural architecture of both accretionary prisms and collisional thrust belts. Facies patterns likewise affect the three-dimensional permeability structure of the convergent margin. Fluid flow and mass balance within accretionary prisms represent important SGPP themes. Our ability to predict and model hydrologic properties will improve considerably if the causes and timing of facies changes can be constrained. Thus, a strategy of including active-margin transects in the comprehensive study of sea level compliments several other SGPP goals. Because of extensive deformation, the thrust belts themselves are poor targets for investigations of sea level. On the other hand, large subsiding forearc basins, at relatively shallow water depths, should provide a record of the regional-scale adjustments of the margin to eustatic cycles. Once the record of forearc-basin sedimentation is documented, the same time-frame of eustatic and tectonic cyclicity can be extended to evaluations of the adjacent trench-wedge and accretionary prism.
4. A temperate-water carbonate system, such as on the South Australian margin: To study the development of insitu carbonate production and deposition in response to sea-level change. The on-land geologic record contains massive carbonate sequences that are interpreted as having been deposited in temperate-water carbonate environments. SGPP feels that the a transect drilled in a modern temperate-water carbonate environment through a Neogene sequence will furnish valuable information to better understand the response of these ancient systems to sea-level fluctuations, as well as providing data to interpret the processes by which they have developed in the geologic past.

Ideally, an adequate program linking sea-level to facies architecture would constitute one dedicated leg per year.

SGPP s Vision Beyond 2003

To date, only the Miocene "icehouse" period has been drilled for SGPP sea-level studies. Additional work on the Neogene stratigraphic record will be required beyond 2003 to establish global synchroneity, as extensions of the strategies outlined above. Many of these objectives can be achieved with existing technology. However, sites in extremely shallow water will require alternate platforms, and advance technology will be necessary for adequate core recovery within shallow-water carbonate sequences. In addition, as a long-term goal, the SLWG report recommends that drilling transects in different climatic periods ("doubthouse" and "greenhouse" periods) be achieved. These are deep targets on continental margins. Thus, SGPP's vision for deep ocean drilling beyond 2003 to study sea-level questions requires a drill ship with a riser capability for drilling on both passive and active continental margins to penetrate depths currently beyond the capability of the *JOIDES Resolution*.

Fluid Flow & Geochemical Fluxes

Introduction

Large-scale circulation of fluids within the oceanic lithosphere is of fundamental importance to global geochemical budgets. The interaction of fluids with oceanic sediment and basalt is a first-order process affecting the cycles of elements and determining the transfer between geochemical reservoirs. A major manifestation of the thermally-driven migration of fluids through oceanic sediments and underlying oceanic crust is the mobilization and concentration of metals, locally to economically important levels. In this sense, metallogenesis represents a special case in which an otherwise diffuse fluid-flow field is highly focused to yield considerable amounts of metal precipitation. Fluid circulation and the transport of solutes and gases by fluids are major processes occurring in many, if not all, environments beneath the seafloor, and, because the discharge regions at all margins are submerged, ocean drilling is essential. The study of fluid flow through and out of both active and passive continental margins and mid-ocean ridges is an essential component of other earth science programs, such as MARGINS and InterRidge, which will benefit from interaction with a fluids driven ODP-SGPP program.

Although not as well documented as for tectonically activity settings, there is a growing realization that fluid flow processes are also prevalent in passive continental margins and isolated carbonate platforms and atolls. Recognition of the fluid flow in such settings has lagged significantly behind studies in accretionary prisms and mid-oceanic ridges because the identification of the processes and the causal mechanisms are ill defined. For example, in carbonate settings there are not the number of exotic tracers of fluid movement that have been documented in accretionary prisms and close to the ridge axis. In addition, geothermal gradients are typically reduced and, therefore, it is difficult to recognize flow by this often-used thermal parameter. Frequently, evidence of fluid flow processes goes unnoticed.

Passive margin fluid movement associated with continental margin processes has often been recognized by reductions in the salinity of pore fluids in sediments. It has been suggested that one kind of pump that may be important is driven by the large head difference between the margin and the adjacent land mass. In association with evaporites, this pump is aided by negative buoyancy as the meteoric waters become saturated in salt, become denser than sea water, and seek to escape in those aquifers that outcrop below sea level on the continental slopes.

Carbonate platforms are thick accumulations of calcium-carbonate-rich sediments produced by benthic organisms in relatively shallow, warm waters. Although dominantly composed of calcium carbonate, they differ from pelagic carbonate-rich sediments because they are assemblages of metastable carbonate minerals (aragonite and high-Mg calcite), and consequently tend to be more susceptible to diagenetic alteration. Although carbonate platform occurrences are limited in the modern ocean, analogous sedimentary carbonates comprise a major portion of the Paleozoic record. In addition, they form a significant proportion of petroleum reservoir rocks (~60%) and host important ore minerals.

Most studies of shallow-water carbonate diagenesis have been confined to Pleistocene-to-Recent Sediments, the results of which are often extended to ancient carbonate rocks. Attempts to model major diagenetic processes, such as dolomitization, cementation, and formation of secondary porosity and permeability, indicate the necessity for extensive fluid flow (thousands of pore volumes of fluid), especially along the flanks of the platforms. Several possible mechanisms for generating such flow have been proposed. Among these are geothermal convection, fluid density differences, and hydrostatic pressure differentials. These hypotheses point to the importance of quantifying fluid flow within sediments, identifying driving mechanisms for generating this flow, and assessing compositional changes associated with chemical and microbial diagenesis.

An immediate high-priority technology requirement for SGPP's fluid flow program is the sampling of in situ fluids in indurated lithologies. This would likewise include the sampling of high-temperature fluids. Normal studies of pore fluids in semi-consolidated sediments have been accomplished by squeezing pore fluids and analyzing the waters. The present technology for retrieving pore fluids from sedimentary sequences has provided invaluable information on diagenetic processes and geochemical fluxes. This knowledge needs to be expanded into more lithified sections of the rock record, but, because of the nature of the sequences, other fluid recovery strategies need to be employed. One of these is simply to sample the borehole fluids after the drilling has been completed. Such methods only produce meaningful data if the formation is overpressured or the bore hole is in equilibrium with the formation and there is minimal exchange between the bore hole and the overlying sea water. An underpressured formation would draw bottom water into the hole and show an invariant profile throughout. A second method would be to pack off an interval using a straddle packer and pump fluid from the formation until a composition considered to be representative was obtained. An additional high-priority objective is to penetrate an active bare-rock site to sample fluids and rocks and make physical measurements (porosity and permeability) in order to understand the processes of convection, chemical reactions and fluxes. This drilling would require an operational Diamond Coring System (DCS) system.

Accomplishments to Date

One of the major achievements of the first eight years of the ODP was the demonstration that fluids moving through and flowing out of the margins and mid-ocean ridges are major contributors to the geochemical fluxes in the lithosphere and hydrosphere. In its original 1990 White Paper, SGPP stated that continental margins, both active and passive, are of the highest priority for drilling during the period through 1994. It was also proposed that a spectrum of modern settings should be investigated in order to evaluate the possible range of controls on ore formation. Although process and some variability have been identified, SGPP proposes that the next goals must be to quantify the processes, including types of fluid flow, geochemical reactions and fluxes, fluid fluxes, and continue exploring for variability.

To date, major accomplishments in SGPP's fluids program in various tectonic environments are:

1. Accretionary prisms: Several programs have been drilled; N. Barbados Ridge (Legs 110 and 156), Peru Margin (Leg 112), Nankai (Leg 131), Peru-Chile Triple Junction (Leg 141), and Cascadia Margin (Leg 146), as well as earlier DSDP Legs 67 and 84 in the Central America Margin. Process and some variability have been identified.
2. Volcanic arcs: Mariana Forearc (Leg 125) drilled serpentinite seamounts and documented occurrence of fluids derived from dehydration of the subducting slab, 60 km below.
3. Ridge flanks: Costa Rica Rift (Sites 504, 677, 678, and 896) (Legs 111, 140, and 148) documented the occurrence of upwelling and downwelling zones of sedimentary pore fluids. DSDP Leg 85 in Central Equatorial Pacific documented large scale fluid advection over 1.5 million square km, with little chemical change
4. Ridge crests:
   a) Sediment covered spreading centers: Sedimented Ridges I (Leg 139) penetrated and sampled recharge zone, "reservoir," and high-temperature upwelling zone. The CORK, an instrumented borehole seal which can be revisited by submersible to read temperature and fluid pressure and to extract fluid samples, was first deployed on Leg 139.
   b) Bare-rock drilling on mid-ocean ridges: Snakepit, MAR (Leg 106) sampled sulfide deposit, but with poor recovery and drilling problems. TAG (Leg 158) will be drilled with the goal of sampling high-temperature upwelling zone, massive sulfide deposit, stockwork feeder zone, and possible fluids.

SGPP 1996-1998 Drilling Program

Recognizing the need to move towards the quantification of fluid flow processes, SGPP proposes that specific goals for the drilling program should be to determine:

1. The effects of fluid flow on sediments and the feedback between sediment architecture, diagenesis and flow
2. The effects of fluid flow on alteration of oceanic crust with feedbacks between alteration and flow
3. The effects of both types of fluid fluxes on metallogenesis

The quantification of fluid flow and fluxes in specific regions with the aid of hydrogeologic borehole experiments should be undertaken. In order to accomplish its shorter term goals for fluid flow studies, SGPP proposes that the following drilling programs be scheduled during the 1996-1998 period: (1) Mass Balance of Costa Rica Accretionary Wedge, (2) Sedimented Ridges II, (3) Hydrothermal Circulation at E. Juan de Fuca Ridge, and (4) Evolution of Oceanic Crust. These drilling programs should have equally strong support from either or both the Tectonics and Lithosphere Panels.

SGPP's ultimate goals for its fluid flow and geochemical fluxes program are to identify pathways of flow, i.e., the sedimentary architecture or "plumbing" of a system; to quantify rates of flow and fluxes in order to establish global amounts of mass and heat transfer; and to determine the diagenetic or alteration potential of fluids with an emphasis on how this might affect the "plumbing" of a system or lead to metalliferous deposits. To achieve these goals, requires the identification of specific environments where discrete aspects of fluid flow processes can be effectively studied. Potential fluid flow programs for the 1999-2003 period could include drilling legs on another convergent margin, on an isolated carbonate platform, and in the Red Sea. A greater emphasize should be placed on more sophisticated hydrogeologic experiments and in situ borehole monitoring.

SGPP s Vision Beyond 2003

As with its sea-level program, SGPP's vision for deep ocean drilling beyond 2003 to study fluid flow questions requires a drill ship with a riser capability for drilling on both passive and active continental margins and in the deep sea to penetrate depths currently beyond the capability of the *JOIDES Resolution*.

Carbon Cycling from the Seafloor to the Base of the Biosphere

Introduction

SGPP interest has been and continues to be in geochemical budgets and the global carbon cycle, which are intimately linked with global climate. The revised SGPP program proposes to evaluate mechanisms driving global change on various time scales through the study of these interactive processes linking the lithosphere, hydrosphere, and atmosphere. A particular emphasis is placed on the carbon cycle because variability in the burial rates of oxidized and reduced forms of carbon in marine sediments is a key mechanism regulating the atmospheric concentrations of CO_2 and O_2 over time scales longer than the turnover of the ocean. In the modern ocean, spatial and temporal variability in accumulation rates of organic carbon (or of other biogenic material and of appropriate proxy-indicators) is directly related to productivity at the sea surface, sediment influx and sedimentation rate, and ocean circulation. Under debate are influences exerted by the redox state of bottom waters and by lateral input of organic matter originating from the continental margins or from land.

Detailed knowledge of the spatial and temporal patterns of carbon burial and the mechanisms of carbon sequestering is essential to the formulation of accurate models for paleoproductivity and defining causal relationships between bio-production and climate change and, hence, regulating atmospheric pCO_2 and pO_2. Developing such models of the paleocean environment is central to our attempt in predicting how human influence will impact future, otherwise, naturally controlled, climate fluctuations. An important key to understanding this is the record of organic carbon that has accumulated and become buried (preserved) in the sediments. Between accumulation at the seafloor and preservation at depth, about 90% of organic carbon is destroyed, leaving a meager record for interpretation. What happens to organic carbon once it reaches and is buried beneath the seafloor is related to microbial activity at depth, which ultimately determines the preserved organic carbon record. In addition, the roles of organic matter productivity and preservation are not completely understood in the formation of organic carbon-rich sediments. For interpretation in many cases, it is the composition of the organic matter that is more important than the actual amount, which is usually the basis for the study of organic carbon-rich sediments.

Paleochemical tracers and accumulation rates of biogenic sedimentary components remain the primary source of information on past global geochemical balances and are elemental for reconstructing past environments. SGPP advocates detailed mapping of organic carbon accumulation and available productivity and environmental proxies in highly-resolved and well-dated sedimentary transects across continental margins and in ocean basins. This strategy will permit a reconstruction of past productivity patterns through the deconvolution of primary fluxes related to productivity and secondary fluxes related to sediment reworking and lateral transport. Creating such records in diverse environments will help identify external climate-related controls, such as eolian, river and nutrient inputs, and internal controls, such as redox conditions and sea level, on the temporal variability in the accumulation of organic carbon in the ocean.

Interdisciplinary studies within the ODP framework would allow integrated geochemical studies to reconstruct anoxia. Whilst the carbon cycle is undoubtedly at the core of this SGPP theme, it is interlinked with the cycling of other elements, such as nitrogen, sulfur and phosphorus. The processes controlling preservation, recycling, and diagenetic fate of these elements in marine sediments are not well understood and can be addressed by ODP as part of SGPP's process-oriented science program.

To advance our understanding of environmental conditions that led to widespread maxima in carbon burial in Mesozoic oceans and marginal seas, SGPP anticipates a need to calibrate the environmental significance of geochemical tracers (and all other available indicators of environment) by investigating modern analogues of organic-carbon-rich sedimentation in the ocean, to test these calibrated tools in datable and highly-resolved organic-rich deposits of Cenozoic marginal seas, and finally to apply those that prove to be robust and unambiguous to Mesozoic organic-rich deposits of continental margins.

Within the realm of ocean drilling, microbiological activity, occurring below the sediment/water interface to depths at the base of the biosphere warranting the drill string, have significant implications for fluid flow, carbon preservation, and nutrient recycling on continental margins. SGPP proposes that a strong emphasis be placed on the study of microbial processes within these thick sedimentary bodies to be able to model its influence on the properties of the sediments, as well as on the overall global carbon budget. Of special interest is the possibility that, after deposition, microbial processes can contribute a continued supply of biomass to the sedimented organic matter to considerable depths within the sequences (100's of meters). Likewise, microbial processes can cause continued diagenetic modification of the organic matter composition to considerable depths. What is the role of bacteria in organic matter diagenesis and preservation in sediments? To what extent do bacteria control geochemical reactions? Various diagenetic processes, e.g., kerogen formation, sulphur incorporation into organic matter, preservation of lipids, are still poorly understood by organic geochemists, perhaps because the significance of biochemical and microbiological processes have not been extensively investigated. In addition to microbial activity within sedimentary packages, bacteria have been observed in hydrothermal fluids venting from mid-ocean ridges. The possibility of microbial communities thriving disconnected from photosynthetic pathways in hydrothermal systems within the oceanic crust adds new dimensions for the study of life at the base of the biosphere. ODP has the opportunity to really contribute to our knowledge in all these areas of deep-sea microbial studies.

Accomplishments to Date

To date, SGPP's carbon cycling program has focused on process oriented studies that aim:

1. To understand the role of oxygen-deficient conditions and biological productivity in determining carbon sequestration in marine sediments
2. To investigate the extent and timing of organic carbon burial in marginal seas
3. To recognise the impact and dynamics of gas hydrate accumulations on the marine carbon reservoir and on atmospheric chemistry
4. To elucidate the impact of nutrient and carbon flux from land to sea mediated by rivers and sediment and carbon burial in adjoining ocean basins

Major accomplishments in SGPP's carbon cycling program can be summarized as follows:

1. Gas hydrates: Because the amount of reduced carbon sequestered in gas hydrates as methane, from both microbial and thermogenic sources, is potentially enormous (possible exceeding 10,000 gigatons), this carbon reservoir is one of the largest, and least understood, in the global carbon cycle. Only very general information is available about the global distribution and composition of gas hydrates, and virtually nothing is known about the dynamics of their formation and destruction in the marine environment. For these reasons, SGPP has specifically designated the drilling of gas hydrates on the outer continental margins as one of its highest global-priority programs. To accomplish this goal, specific technologic developments are needed that pertain to the retrieval of sediments under in situ conditions. SGPP strongly supports the continued development and modification of the Pressure Core Sampler (PCS). Progressive steps forward towards understanding the process of gas hydrate formation have been made with recent drilling on Chile Triple Junction (Leg 141) and Cascadia Margin (Leg 146). A dedicated gas hydrate leg is now scheduled for Leg 164 on the Blake Ridge-Carolina Rise.
2. Organic-carbon cycling: SGPP has in the past advocated research into budget-oriented studies, which investigate spatial and temporal patterns of carbon sequestration in marine sediments to reconstruct the magnitude and patterns of the biological carbon pump, the role of sedimentary fluxes on carbon burial, and sedimentation processes on continental margins changes under Cenozoic "icehouse" conditions of global climate. A strong focus has been on continental margin processes and their teleconnections with the ocean's interior, on mapping the timing and frequencies of changes in carbon burial in the entire ocean, and on the history of carbon sequestration in highly productive marginal seas.

   On productive (upwelling) margins, organic carbon-rich sediments have been drilled on the Peru Margin (Leg 112), Oman Margin (Leg 117) and Santa Barbara Basin (Leg 146). In pelagic high productivity areas, organic carbon-rich sediments have been drilled in the Southern Ocean (Leg 114), Owen Ridge/Arabian Sea (Leg 117), Equatorial Pacific (Leg 138), and North Pacific Transect (Leg 145). A most important result of these studies is that patterns of organic carbon accumulation on the productive margins show a strong link to sea level, regardless of the atmospheric driving mechanism. The Peru shallow sites have low total organic carbon (TOC) accumulation rates during glacials, even though the trade winds and upwelling are assumed to have been stronger. The Arabian Sea upwelling area shows consistently high glacial accumulation rates on the margin (>600 m) and on the Owen Ridge, even though the monsoon was weaker during glacials. Patterns of TOC accumulation on all margins may be dominated by sediment reworking on the shelves and lateral input of exhumed organic carbon to the slopes. Patterns of sediment and organic carbon accumulation in the pelagic interior of the ocean basins (Leg 138) show a strong increase during glacials.
3. Black shales and the anoxia/productivity controversy in epeiric seas, marginal seas, and oxygen deficient environments: Mediterranean sapropels (Legs 107, 160, 161), Antarctic/Cretaceous black shales (Leg 113), Japan Sea (Leg 127/128), NW Australia, Cretaceous black shales (Leg 123), and oxygen-minimum settings (Legs 112/117/146).
4. Strontium-isotope stratigraphy: The application of this stratigraphic tool to deep-sea carbonates represents a new advance in high-resolution chronostratigraphy linked to mid-ocean ridges, continental uplift and erosion.

SGPP 1996-1998 Drilling Program

On the shorter term, SGPP plans to concentrate its carbon cycling program from the seafloor to the base of the biosphere on the evaluation of the influence of organic carbon sequestering in coastal upwelling areas and gas hydrate formation on the global carbon budget. During the 1996-1998 period, SGPP proposes that drilling programs on the California Margin and along the Benguela Current upwelling zone should be scheduled. These drilling programs should have equally strong support from the Ocean History Panel. Depending on the results of Leg 164, a second dedicated gas hydrate leg on either the Peru or Costa Rica margins may be warranted during the 1996-1998 period. SGPP considers its program for the study of gas hydrate formation to be succinctly global in nature and driven by a step-wise accumulation of knowledge upon which each subsequent gas hydrate drilling proposal must build.

SGPP 1999-2003 Drilling Program

The future focus of SGPP's carbon cycling program will concentrate on the following goals:

1. Mapping of temporal and spatial patterns in carbon burial
2. Material cycling on continental margins and its impact on adjoining ocean basins
3. Impact of material eroded from margins on the deep ocean and the role of eolian material in determining carbon sequestration
4. High-resolution productivity reconstructions in relation to climate
5. The role of productivity and anoxia on organic carbon accumulation
6. Impact of rivers on productivity and carbon burial in marine sediments

During the 1999-2003 period, a more complete Neogene record of coastal upwelling sedimentation and carbon transport along specific continental margins needs to be developed. In addition to the amounts of preserved carbon in the sedimentary record, it is important to consider its form and quality. The impact of rivers on productivity and carbon burial along margins should also be considered in this drilling program. An inclusive program to study carbon cycling through a subduction zones is visualized. The interesting questions surrounding methane anomalies in the water column in areas of serpentinized rock deserves consideration for a drilling program in relation to the potential for a significant source of methane emanating from the mantle. Finally, SGPP considers a most essential component of its carbon cycling from the seafloor to the base of the biosphere program for the 1999-2003 period to be the investigation of microbial processes deep in the sedimentary column and their diagenetic implications. In addition, the study of the microbiology within hydrothermal zones is proposed.

SGPP s Vision Beyond 2003

An extension of our knowledge of the record of spatial and temporal patterns of carbon burial and the mechanisms of carbon sequestering back into the Paleogene and Mesozoic must be attempted in order to understand carbon flux through a longer time span. As with its sea-level and fluid flow programs, SGPP's vision for deep ocean drilling beyond 2003 to study questions pertaining to the long-term record of carbon burial requires a drill ship with a riser capability for drilling on both passive and active continental margins and in the deep sea to penetrate depths currently beyond the capability of the *JOIDES Resolution*.

CORRECTED CD-ROM OF DSDP CUMULATIVE INDEX NOW AVAILABLE

A corrected CD-ROM has been issued to replace the one that was sent originally with the boxed set of the "Cumulative Index to the *Initial Reports of the Deep Sea Drilling Project.*"

Because the first compact disc contained a flaw in the Subject Index, a maximum of only nine references were included for any term. Now, the corrected disc will show all relevant references.

The US National Geophysical Data Center produced and mailed copies of the corrected disc to recipients of the complete DSDP index set, which was published in 1991. The US National Science Foundation funded replication of the disc.

If you received the original index set, but have not received the updated CD-ROM, you can obtain the disc without charge from the Publications Distribution Center, Ocean Drilling Program, Texas A & M University Research Park, 1000 Discovery Drive, College Station, Texas 77845-9547, USA. The complete index set, with the replacement disc included, is also available from the above address for US $50.00 postpaid.

Guidelines for Shallow Water Hazards Surveys

Working Group Report

A Report of the JOIDES Shallow Water Drilling Working Group

Mahlon Ball, Chair Report Submitted July 1994

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Summary

During their October 1992 meeting, concern regarding potential for gas blowouts in shallow water settings caused the JOIDES and ODP safety panels to disapprove a number of proposed drill sites on the New Jersey shelf. The special blowout danger in shallow water drilling is that gas, with its attendant threats of fire and explosion, will reach the sea surface at or in close proximity to the drilling vessel. In ODP drilling, this danger is compounded by the drill ship's lack of a blow out preventer (BOP) and limited capability to use weighted drilling mud to contain gas release on a scale comparable to a standard oil and gas exploration rig.

It is PCOM's conviction that passive margin drilling must play a central role in the study of the history of relative sea level variations and that these studies are of scientific merit. This conviction led to PCOM's establishment of a Shallow Water Drilling Working Group. The responsibility assigned this group was to determine the specifications of shallow water hazards surveys necessary to minimize potential for gas blow outs in sedimented shelf drilling.

The main conclusions from this meeting were:

1. Open-hole drilling in shallow water is reasonably safe if proper hazards surveys are conducted and combined with proper data processing and interpretation.
2. Hazards Surveys must be a requirement for ODP drilling on sedimented shelves in water depths of 200 m or less.
3. Sub-bottom penetrations at those depths, without BOP and mud-weight capabilities, must be limited to 1000 m.
4. Operational procedures for shallow water drilling such as: dropping the drill string, monitoring the seabed for gas escape, and safety contingency plans must be developed.
5. Interpretation of the survey data in terms of shallow gas hazards should be made by experts in the field who are also not associated with the scientific proposals justifying the program.
6. ODP's slim, open-hole drilling from a dynamically positioned vessel is a relatively safe method for shallow water operations but blowouts must be avoided.

1. Introduction

1.1 Background

During their October 1992 meeting, concern regarding potential for gas blowouts in shallow water settings caused the JOI and ODP Safety Panels to disapprove a number of proposed drill sites on the New Jersey shelf. The special blowout danger in shallow water drilling is that gas, with its attendant threats of fire and explosion, will reach the sea surface at or in close proximity to the drilling vessel. In ODP drilling, this danger is compounded by the drill ship's lack of a blow out preventer (BOP) and capability to use weighted drilling mud to contain gas release on a scale comparable to a standard oil and gas exploration rig.

1.2 Shallow Water Drilling Working Group

It is PCOM's conviction that passive margin drilling must play a central role in the study of the history of relative sea level variations and that these studies are of scientific merit. This conviction led to PCOM's establishment of a Shallow Water Drilling Working Group. The responsibility assigned this group was to determine the equipment, dimensions and costs of shallow water hazards surveys necessary to minimize potential for gas blow outs in sedimented shelf drilling.

The Shallow Water Drilling Working Group (SWDWG) met in February 1993. Attendees included representatives of PCOM, PPSP, ODP-TAMU, SSP, TEDCOM, and industry, with members of SEDCO-FOREX, site survey companies, well control specialists and major oil companies. Important written contributions to this meeting were made by Deminex; Vernon Greif, SEDCO-FOREX; Colin Leach; U.S. Minerals Management Service; Joar Saettem, IKU, Norway; Well Control and System's Design; Alister Skinner, British Geological Survey and Peter Trabant, Marine Geohazards consultant.

1.3 Flexibility

The following guidelines are open to change. Regulatory and scientific differences make change a necessity. For example, the requirements for presence of BOP versus water depths, for nations bordering the North Sea, vary from 25 to 400 m. Evolution of geophysical equipment used in high resolution hazards surveys is in a constant state of flux. In general, state of the art equipment will be required for ODP shallow water surveys. This means that our guidelines will have to be updated continually.

1.4 Acknowledgments

The following made important contributions to the development of this report:

Harold Barber	Seascan
Jake Booth	Mobil Oil
Earl Doyle	Shell Oil U.S.
Craig Fulthorpe	U.T.I.G.
Vernon Greif	Sedco-Forex
James Hooper	McClelland Engineering
Larry Kuhlman	Neal Adams Firefighters
Clyde Lee	Sytech
Gary Marsh	Shell Oil U.S.
Chris Nehring	Sedco-Forex

Particularly valuable assistance was given by Alister Skinner of the British Geological Survey who provided guidelines for multichannel seismic data acquisition written by P.M. Walker of Shell U.K. that are adopted for our use. In a similar manner, Earl Doyle's specifications for quality control of multichannel hazards surveys are followed in this report. Contributions by Dietrich Horn (PPSP) of Deminex and Jack Keinzle of the U.S. Minerals Management Services are also incorporated in the procedures adapted by the SWDWG.

2. Shallow Water Site Survey Guidelines

2.1 Site Survey Objectives

The objective of a shallow water gas hazards survey (SWGHS) is to identify occurrence of gas, from the sea-floor down to at least 1,000 m, at a site proposed for ODP drilling. SWGHS is required at proposed sites to allow the Science Operator (ODP-TAMU), together with the JOIDES PPSP and the ODP-TAMU Safety Panel, to properly evaluate the safety aspects of a site and to determine whether drilling should be undertaken or not. These guidelines are applicable at sites where the water depth is less than 200 metres and where the Science Operator has not specifically waived the requirement for a shallow water gas hazard survey.

<u>ODP-TAMU shall be involved with the proponents in the planning of Shallow Water Gas Hazards Surveys and shall be responsible (both technically and fiscally) for quality control during data acquisition, processing, and interpretation of Shallow Water Gas Hazards Surveys of highly-ranked proposals that PCOM may wish to schedule for drilling.</u> Funds to conduct Shallow Water Gas Hazards Surveys (including ship time, data acquisition, and data processing) are the responsibility of the proponent(s). In order for the Science Operator (ODP/TAMU) to be involved in the planning of the SWGHS, proponents should contact the Science Operator (Director's office) at the earliest possible stage in their planning.

Shallow water is defined as water depths less than 200 m. The reason for selecting this depth is that experience in the oil industry has shown that gas blowouts at greater depths are not catastrophic to the drill rig, whereas blowouts from depths of less than 200 m can be.

Evidence of shallow gas can be found in sea-floor morphology (pock marks), in natural gas leaks at the sea-floor, or in seismic reflection data. Judd and Hovland (1992) show excellent examples of how these data can indicate shallow gas.

It is assumed that prior to the SWGHS proponents will have acquired seismic data sufficient to justify the scientific objectives and to specify actual drill sites to address the science objectives. The SWGHS specifications are designed so that safety aspects of specific sites can be evaluated. In general the SWGHS will provide the proponent with images of the scientific targets that are better than those acquired previously. The proponent should bear in mind that sites may have to moved for safety reasons and that alternate sites could be picked from the SWGHS, providing the area covered by the survey is large enough to do this.

The surveys will have seven general requirements, which are outlined below and described in detail in subsequent sections.

- 2.2 Accurate navigation
- 2.3 A dense survey grid
- 2.4 Side scan surveys to identify sea-floor features
- 2.5 High resolution MCS imaging of the sub-surface down to at least 1,000 m
- 2.6 Independent quality control of MCS data acquisition
- 2.7 High resolution imaging of the sub-surface down to about 100 m
- 2.8 Independent interpretation of the data by an expert in the field of shallow gas

2.2 Navigation

Positioning data should be acquired by a method which allows absolute accuracy of about 10 m. Differential GPS or mobile electronic systems are acceptable.

Positioning data requires processing on-line to allow the survey vessel to run along the required line pattern and for control of seismic shot interval and position. Raw positioning data should also be recorded to allow post-processing. Post-processing should remove spurious data, correct errors (if any) and take advantage of smoothing techniques. It also provides a quality control check on the real-time acquisition and information on potential systematic positioning biases.

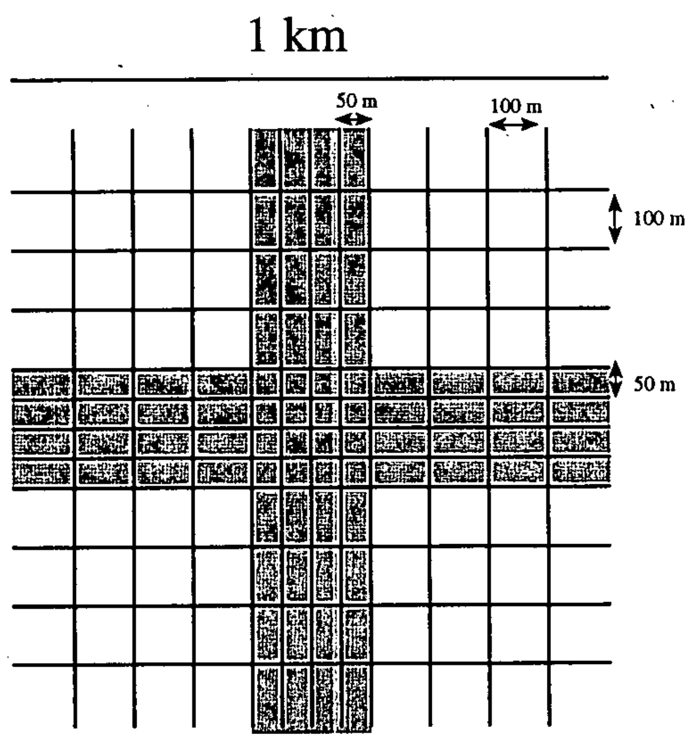

Figure 1. Minimum grid spacing for MCS gas hazards site survey. The proposed site is at the center of the grid.

Care should be taken to ensure that the correct offsets are applied in the computation of all points such as antenna and sensor positions.

2.3 Survey Grid

It is required that at the minimum an area of 1 km by 1 km, centered on the proposed site, be surveyed with a line spacing shown in Figure 1.

Several factors must be considered when defining the survey area:-

a) If the final well location is not precisely known, the area surveyed should cover all possible locations

b) Should possible gas accumulations be detected, the survey area should be large enough for the identification of alternative locations

c) If several closely spaced wells are likely, it may be more economical to perform one large survey, rather than several small ones

Even if there is little flexibility to move the final well location, surveys of very small areas are not cost effective or useful. Very short seismic lines (of a few hundred meters) are difficult to interpret and take almost as long to acquire as lines of reasonable length (in excess of 1 kilometer).

If top hole well logs are available from nearby wells, lines should be acquired to tie these wells to the location for correlation purposes. Even if no top hole well data is available, tie lines may still be useful to relate drilling conditions at the proposed location to those at an already drilled location.

The recommended minimum survey area for shallow gas detection is 1 kilometer by 1 kilometer of full fold coverage, centered on the proposed location. This surveyed area should permit a recommendation for a move of location if necessary. However, features may be larger than 1 kilometer, so to assist in interpretation of the data, a few longer (several kilometers) lines should be considered. These could be tie lines to adjacent wells and lines through the proposed location.

Line spacing will dictate the ability to detect features of limited lateral extent. To ensure detection of small gas pockets at shallow depths, a line spacing of 50 meters around location is recommended. This could be relaxed to 100 meters line spacing away from location. Should the location need to be moved away from shallow gas to an area of 100 meters spaced lines, additional infill lines to 50 meters may be required, depending on local geology. Should no suitable drilling location be found within the 1 kilometer survey area, an additional survey will be required, but the longer lines may act as a basis for selection of the new location.

The survey grid should be oriented such that one seismic line heading is perpendicular to the geological strike. This will generally be the primary 2D exploration seismic line heading. Should the location need to be moved away from shallow gas, and the orientation of the lines has been selected to coincide with the heading of 2D exploration seismic data, it may be possible to move the well location within the survey area to an alternative position suitable for the scientific objective. If 3D seismic data is available, coincident line heading will not be required.

2.4 Sidescan Sonar

Evidence of shallow gas can be found in sea-floor morphology (pock marks), in natural gas leaks at the sea-floor, or in seismic reflection data. Judd and Hovland (1992) show excellent examples of these data can indicate shallow gas. Side scan sonar data play an important role in quantifying the morphology of the sea-floor and are necessary data in these surveys.

A dual channel side scan sonar linked to a graphic twin channel recorder shall be used to provide information on the sea-floor morphology and to identify and locate seabed obstructions and other local features. Suggested specifications and operating variables are listed below:

Operating Parameters:

Beamwidth: .... Horizontal: 1.2° ;Vertical: 50°

Beam Depression: .... 20° below horizontal

Operating Frequency: .... 105 ±10 kHz

Cover: 200%

Positioning: .... to 10 m accuracy

Data should be of good quality, achieving energy return to 200 meters. Assessing the threshold for detection of seabed contacts is particularly difficult with sonar on account of the wide range of variables. Apart from consideration of record quality generally (such as propeller noise and operator ability), these variables include the shape, composition (hardness) and attitude of the contact, the contact range, the towing height of the sensor, the nature of the surrounding seabed and vessel speed. Linear targets such as a thin cable a few centimeters thick can often be detected, whereas sediment patches might be a few meters across. As a very general guide, at the commonly used 200 meter per channel range and in reasonably favorable operating conditions, seabed projection becomes detectable at about 20 cm elevation. A plotting accuracy of 10 meters is considered realistic.

Accuracy can be improved in a number of ways. These include fish tracking systems, running lines in opposite directions and advanced plotting techniques. On the other hand, manufacturer's tables relating, for instance, beamwidth and tow speed to detection probability for a given range need to be treated with caution, since many arbitrary assumptions have to be made. We desire minimum detectable projection at about 50 cm.

2.5 High Resolution Imaging of the Subsurface from the Seafloor Down to at Least 1,000 m

2.5.1 Objective

The objective is to identify all gas accumulations within the upper 1000 meters of the sub-seabed floor. In practice, there are limits to vertical and lateral resolution, and resolution will degrade with increasing sub-seabed depth. A realistic objective in the upper 1000 meters of sub-seafloor is the resolution of potential gas accumulations of at least 5 meters thickness, and 200 meters diameter aerial extent. Gas accumulations of less than 5 meters thickness will be detected (1 meter thickness in ideal conditions) but the top and bottom of the unit may not be resolvable. With this objective at 1000 meters sub-seabed, smaller gas accumulations will be detected in the shallower levels. Acquisition and data processing parameters should therefore be specified to provide optimum vertical and lateral resolution throughout the objective interval.

In principal (and in practice) it is possible to use seismic sources and receivers with a bandwidth from about 10 Hz to 2+ kHz. Frequencies at the upper end of the spectrum do not penetrate much below a few tens of meters, but they can be used to study the upper tens of meters of the section. Frequencies at the lower end of the spectrum penetrate more deeply and are used in the MCS mode to study the deeper section. In a SWGHS both data are required. They can be acquired by either using a single system (broadband MCS system with appropriate processing) or two separate systems (say an MCS system and a deep tow boomer or an MCS system with a ship mounted 3.5 kHz system). Specifications for both are supplied in this document, but the data aquirerer should be aware of these options.

Even with data acquired to the limits of available technology, these surveys do not guarantee that all shallow gas accumulations will be detected. Due to limitations in resolution and data interpretation, the surveys should be viewed as a preventive measure, reducing the risk of encountering a gas accumulation.

2.5.2 Equipment

To achieve the objective, multi-channel, digitally recorded, high resolution seismic data are required. The parameters listed below provide minimum acquisition standards for shallow gas detection. Although local geological conditions may allow relaxation of these standards, they should provide acceptable seismic data in most areas.

2.5.3 Seismic Source

The outgoing seismic signal should be stable and, for a source tow depth of less than 3 meters, have the following far field characteristics within the bandwidth of the operational filters:

a) Peak-to-peak amplitude in excess of 3.5 bar meters
b) Bandwidth of at least 20 to 170 Hz at -6 dB
c) Primary to bubble ratio in excess of 15:1
d) Repetition rate of no more than 3 seconds
e) Preferably minimum phase

Examples of sources meeting these specifications are Seascan's "Tricluster 80" or Geoquip's "Q-10".

The seismic controller must synchronize guns to fire within 100 microseconds of each other. Examples of source controllers are Reftek Model 43 or Sino Technology Model ECS-2.

2.5.4 Hydrophone Streamer

a) 48 groups minimum
b) Group length of 12.5 m
c) 600 meters minimum active length
d) Sensitivity in the order of 5 volts per bar (transformer coupled)
e) Depth controllers and indicators at least every 100 m
f) Equal spacing of hydrophone elements throughout the streamer

Example is Teledyne Model 29500 Programmable Hydrostreamer cable. Filter settings are 27 Hz (low cut) and 512 Hz (anti-alias).

2.5.5 Acquisition Parameters

Data will be digitally recorded with a system having appropriate resolution and bandwidth. An example is Texas Instruments DFS V (or approved equivalent) configured for a shot interval every 6.25 meters and using a Raytheon LSR 1807M graphic recorder (or approved equivalent) to do a read after write display of the near trace. Record length 1.5 sec (sub seafloor), filter (approximate) low cut 10 Hz and 500 Hz anti alias, display constant horizontal scale at approximately 1" = 150 m.).

The recommended minimum seismic acquisition standards for shallow gas surveys are as follows:-

a) Sample rate: .... 0.5 millisecond
b) Record length: .... 1.5 seconds
c) Shot interval: .... 6.25 meters
d) Number of channels: .... 48 minimum
e) Streamer group length: .... 12.5 meters
f) Source and streamer tow depth: .. 2.5 meters
g) High cut filter: .... 512 Hz
h) Low cut filter: .... 27 Hz
i) Source-near trace offset: .... minimum (maximum offset should be half water depth)
j) Maximum feathering angle: .... 6 degrees
k) Streamer noise levels (RMS): .... 8 microbars with bursts of up to 20 microbars. (8 microbar level may be relaxed on near traces and near depth controllers)

Specifications for streamer noise levels are of particular importance to ensure adequate signal-to-noise ratio within the seismic data. They should be reviewed on a site specific basis while the seismic data is being acquired, by assessment of signal-to-noise, throughout the objective interval.

In general, interference in excess of 25 microbars RMS can be tolerated as long as it is in-line to the streamer, i.e. from ahead or astern. Very little noise can be tolerated from broadside, i.e. the beam, and the 8 microbars RMS specification should be applied. For noise arriving between the in-line and broadside cases, the range of geological dips expected and seismic velocities will dictate the arrival angles of acceptable noise levels. Interference should also be reviewed, therefore, on a site specific basis by assessment of signal-to-noise. If possible, lines should be shot such that the interference arrival direction is in-line.

To further improve resolution, a few lines with source and streamer towed at very shallow depths (1 meter), and shorter streamer group lengths (6.25 meters) should be considered. These lines require a seismic source which will provide suitable high frequencies when towed at a shallow depth. Acquisition may be difficult due to the low weather tolerance of the shallow source and streamer tow depths. However, at least two lines over the drilling location should be considered, in addition to the full grid of 2.5 meter tow depth lines.

2.5.6 Data Processing

The objectives of processing seismic data include improvement of signal-to-noise ratio, improvement of vertical and lateral resolution, suppression of multiple events, and enhanced display of data.

Processing of data should be undertaken with extreme care since it is possible to create and destroy events on the seismic record. As a rule of thumb, the minimum processing of data should be undertaken and processing which destroys relative amplitude information must be avoided. Careful analysis of processing tests permits selection of those processing steps which enhance the data. When undertaking processing tests the area selected should be representative of the site. Care should be taken to alter only one variable at a time so the effect can be assessed. Processes should not be applied unless there is obvious benefit. On occasion, even though a process may be of obvious benefit in one way (e.g. multiple suppression) it may be disadvantageous in another (e.g. data suppression and noise creation).

Careful velocity analysis is of particular importance to ensure correct CMP stacking of the data. Velocity analyses should be undertaken at locations chosen with reference to the local geology. The minimum interval should be every 500 meters along the seismic lines. In some areas, where the geology is rapidly changing, (e.g. channels, salt domes) velocity analyses maybe required more frequently with detailed velocity plots such as those offered by Sytech Corporation.

Velocity analyses will be severely degraded by significant lateral velocity variations, e.g. gas charged sand. This can be particularly important for stacked anomalies, and a more careful approach to velocity estimation is necessary if data are to be stacked correctly and reflector amplitudes preserved.

The recommended minimum processing sequence is:-

a) Demultiplex
b) Designature
c) Gain recovery
d) Deconvolution before stack (DBS)
e) Normal Moveout (NMO)
f) Mute
g) Stack
h) Deconvolution after Stack (DAS)
i) Time Variant Filter (TVF)
j) Relative amplitude display
k) Equalized display

Seismic processing systems are available, which allow seismic data processing on-board the vessel, sometimes on-line. These systems are very useful for quality control purposes. However, the on-board processed data should be used with extreme care for interpretation as the processing may have been undertaken by personnel inexperienced in seismic processing, and without adequate quality control. Processing and plotting packages may also be less sophisticated than those onshore.

2.5.7 Interpretation

Interpretation of data for shallow gas detection is subjective and should only be undertaken by experienced personnel. All sources of available data should be incorporated. Wherever possible this should include top hole well data, borehole data, exploration seismic data, adjacent site survey data, regional geological data, and other knowledge of the area. The interpretation of all the data sets acquired during the survey should be carefully integrated for the overall interpretation of the survey area.

Interpretation of the site survey data within the regional framework is important for a full understanding of the geology and potential hazards. Input from the proponent may be useful at this stage, but responsibility for the final interpretation remains with the Science Operator.

2.5.8 Conventional Seismic Analysis

One characteristic seismic response of a gas charged sediment is a high amplitude reflection, although under certain conditions, low amplitude reflections are also possible. Theoretically, the reflection should also be phase reversed where gas is present, but this may not be apparent. Other indicators of gas in sediments are masking of underlying reflection and 'pull down' of underlying reflection, caused by the seismic wave passing through the lower velocity gas pocket. In practice these last two indicators are rarely seen, as they are very sensitive to the geometry of the acquisition spread with respect to the size and depth of the gas pocket. Consequently, identification of possible gas pockets primarily depends on identifying anomalously high amplitude reflections.

High amplitude reflections are caused by a strong impedance contrast. Impedance depends upon the seismic velocity and density of the strata. Therefore, strong impedance contrasts may be purely of lithological origin rather than due to gas accumulation. Constructive interference of reflected seismic waves may also cause high amplitude reflections (tuning effects). The more resolute the seismic data, the easier it is to discriminate genuine high amplitude events from tuning effects.

A small proportion (about 5 percent) of gas in a sediment will cause a high amplitude reflection of similar magnitude to that caused by a large proportion of gas (say 75 percent), so it is difficult to directly quantify gas content from the seismic response. If a closure can be mapped, and the top and bottom of the reservoir unit detected, gas overpressure (in excess of hydrostatic pressure) caused by the height of the gas column can be calculated. However, this is a simplistic approach, based on hydrostatic pressure variations only. It also assumes accurate detection of the top and bottom of the reservoir. Predictions of gas pressures based upon seismic data should be used with extreme care.

2.5.9 Seismic Attribute Analysis

Seismic attribute analysis, which includes variation of amplitude versus offset (AVO) effects, may assist in the discrimination between seismic events caused by shallow gas accumulations and those caused by lithology, e.g. lignite.

Seismic attributes such as increased reflection amplitudes, phase reversal, high frequency loss, and low velocities can be indicative of shallow gas accumulations. The ability to detect variations in these attributes can be enhanced by attribute analysis and display. However, variations in these attributes can also be caused by lithological changes and seismic processing, so interpretation based upon attributes should be undertaken with caution.

AVO effects are generated by changes in plane-wave reflection coefficients as a function of angle of incidence AVO variations can be caused by many factors (e.g. reflection coefficient, array attenuation, tuning, noise, spherical spreading, absorption, emergence angle, reflector curvature, hydrophone sensitivity, and instrumentation and processing). With care, AVO analysis may assist in distinguishing gas related amplitude anomalies from other types of anomalies. In general, over the range of angles of incidence typical of rig site survey data, the top of a gas charged sand layer will show a marked increase of amplitude with offset, whereas a water charged sand will show a very small decrease of seismic amplitude with offset.

2.5.10 Calibration

Direct calibration of the data in the form of nearby top hole well data or borehole data is the most useful tool for assessing the significance of the seismic response and should always be carefully integrated with the data.

Where the geological structure and interpreted lithologies provide a potential trap and no direct calibration is available, anomalous amplitude reflections should always be assumed to be related to gas accumulations.

2.5.11 Depth Conversion

The conversion from seismic travel time to depth below seabed, based on stacking velocities or interval velocities, is accurate to better than 5 percent of the depth when determined with care. Depth predictions can be further improved if top hole well data is available.

2.5.12 Workstations

The use of workstations can assist in the interpretation of seismic data for shallow gas detection. Workstations allow expansion of data displays in areas of concern for easier identification of shallow gas indicators. Seismic attributes can be examined using color displays such as color coded amplitude, instantaneous amplitude, instantaneous phase, and instantaneous and averaged frequency.

Using workstations, tuning effects can be more easily discriminated from high amplitudes caused by shallow gas, on the basis of changes in relative amplitude along the reflector.

2.5.13 Shallow Gas Indicators

The following list is based upon a list provided in the AAPG Memoir 42.

The interpreter should look for the following indicators of shallow gas. Of these, item (a) is the prime indicator.

a) Is the reflection from the suspected reservoir of anomalously high amplitude?

b) Is the amplitude anomaly structurally consistent?

c) If of anomalously high amplitude, it there one reflection from the top of the reservoir and one from the base?

d) Do the reflector amplitudes of the top and base reflections vary in unison, decreasing at the same point at the limit of the reservoir?

e) Is a flat spot visible?

f) Is the flat spot horizontal or is it dipping consistently with gas velocity sag?

g) Is the flat spot unconformable with the structure but consistent with it?

h) Is the flat spot located at the downdip limit of anomalously high amplitudes?

i) Is a phase change visible?

j) Is the phase change structurally consistent and at the same level as the flat spot?

k) Is there a low frequency shadow below the suspected reservoir?

l) Is there an anomaly in moveout derived interval velocity?

m) Is there evidence of pull down or gas velocity sag on underlying reflectors?

n) Is a study of amplitude versus offset on the unstacked data likely to assist?

o) Are there indications of gas migration on the shallow gas (or other) survey data?

In practice, any one indication can be spurious. Shallow gas interpretation on seismic data necessarily involves accumulation of evidence. The more positive answers to the above points, the greater the confidence in the identification of shallow gas.

2.5.14 Reporting

Reporting should be concise and relevant to the survey objective. Consideration should be given to all potential users of the report and any information they require must be readily accessible. Speculative interpretations, unless substantiated by published data should be avoided.

The objective of a shallow gas survey is to identify and map possible gas accumulations. The report should therefore clearly indicate the depth and lateral extent of any such accumulations. Any information used in the interpretation of the data and assessment of the shallow gas potential should be included. Whenever possible, top hole well data should be used to calibrate the data and improve the interpretation.

Interpretation of the seismic data may also be useful for other aspects of drilling such as casing setting studies and detection of potential zones of difficult drilling. The report should therefore clearly indicate the depth and lateral extent of any relevant features e.g. sub-seabed channels, and a prognosis of lithology throughout the objective depth interval.

The reporting should provide a brief but clear statement of expected drilling conditions at the proposed location. This statement should not be confused by discussion of features in the survey area which have no relevance to drilling at the location. It is recommended that a one-page summary of this information is provided in the report.

Topics to be addressed by the report should include:-

a) Summary of results (including interpretation)

b) Results (including interpretation)

c) Operations

d) Calibrations

e) Data reduction and processing

f) Survey equipment

g) Data quality

2.5.15 Charting

Recommended chart scale is 1:10,000.

Charting should include the following:

a) Seismic shot point.

b) The lateral extent of anomalous amplitude reflections presented in time (TWTT) and depth below sealevel or seabed. For clarity of presentation, several charts may be required.

c) Depth below mean sealevel to reflections of interest if there is a potential structure.

d) Shallow faulting if this is relevant to potential shallow gas distribution.

e) Lateral extent and depth of any features which may affect drilling operations (e.g. channels).

f) Interpreted profiles through the proposed location, highlighting potential hazards and significant soil units.

2.6 Quality Control Specifications

Quality of data acquisition for SWGHS shall be controlled by the Science Operator. The parameters that are important in terms of quality control are described in the sections 2.6.1 to 2.6.14

2.6.1 Cable Noise

Cable towing noise at normal shooting parameters will be recorded using production filters at fixed gain on the field tape during minimum straight line run-in of one and one-half cable lengths at start and finish of each line. Recording period will be of a normal record length during which time the source will not be activated.

Cable noise will be measured on any hydrophone group at the discretion of the quality control supervisor using multi-channel paper monitors and the recording filter in use. One channel will carry a 20 Hz reference oscillator signal, which when passed through the recording system, will be calibrated to produce a measured and quantified voltage level in microvolts for the purpose of determining streamer noise.

Cable noise in microbars RMS is defined as peak to peak noise of the cable, when operating under conditions described above, at the recording amplified input in microvolts RMS divided by sensitivity of the detector group in microvolts per microbar when loaded with cable and amplifiers.

Average cable noise will not exceed 5.0 microbars RMS equivalent, for a 12.5 m group length except for groups that are adjacent to depth controllers, or tail buoy, or less than 200 meters offset from the stern of the ship, where average noise of 8 microbars RMS will be tolerated.

Coherent noise from the survey vessel itself, or from other sources (rigs, pipelines, or other vessels) shall be treated with the same limitations as stated above assuming a constant amplitude, in the case of amplitude decreasing with time, a maximum of 8 microbars as averaged over a 250 ms period beginning with maximum amplitude will be accepted.

Seismic interference will be accepted only within the following limitations on: near before far traces equal to 8 microbars; far before near traces equal to 18 microbars; all traces within a 250 ms period equal to 4 microbars; where these value shall be the maximum amplitude experienced with the period of interference.

Residual shot energy at normal firing cycle will be recorded in the same manner as outlined above for cable noise for 10 seconds after record start at least once per day. RPM of propeller shaft, ship speed in knots, sea state, time, date, SOL, EOL, and line number will be annotated on noise strips.

2.6.2 Defective Traces

A seismic trace will be considered as defectively recorded if:

a) system noise, including all wiring from hydrophones to tape recording heads exceeds the previously mentioned quality control specification when all normal shipboard equipment is operating
b) it is dead, wild, intermittent, or more than 6 dB down relative to contiguous traces,
c) polarity does not conform to SEG standards as defined in 7.0 below,
d) its amplitude is distorted or its pulse envelope leads or lags more than 1 ms when input is paralleled,
e) electrical leakage is exhibited or cable insulation between pairs and from ground is less than 0.5 megohm,
f) it fails to met and pass manufacturer's instrument or able quality control tests.

2.6.3 Cable Depth

Cable depth transducers will be spaced along the streamer at a maximum interval of 100 m.

Specified mean cable towing depth is 3 m or as agreed in writing.

When a change in cable depth is authorized due to weather or other circumstances, the depth may only be changed upon completion of a given line. No line shall be recorded with more than one cable depth. Maximum deviation from specified streamer towing depth at any transducer is plus or minus 1.0 m.

Depth transducers will be zeroed and calibrated whenever the streamer is deployed.

2.6.4 Offset

Offset is to be defined as the distance between the center of the energy source array and the center of the nearest active group, and will be approximately 150 meters to facilitate noise isolation for digital streamer recording. Direct water arrivals will be digitally recorded on magnetic tape on auxiliary channels at every shot from hydrophones at a minimum of four positions along the streamer. These may be recorded on a single channel.

2.6.5 Misfires

The following will be considered misfires:

a) loss of magnetic recording on digital system
b) loss of time zero or signature pulse
c) more than 7 parity errors on one recording
d) defective traces as described in 2.6.2 above
e) loss of more than 10% of total air gun array volume, unless there is access to a signature model to indicate wavelet being utilized, and approval to continue has been gained from the on board quality control supervisor
f) a minimum of 1900 psi must be maintained
g) a spread of more than plus or minus 1.0 ms among individual acoustic pulses of units of the source array
h) autofiring or misfiring of units of the source array
i) variation in depth along streamer between adjoining transducers exceeding 1.0 m except during or immediately following adjustment of controllers
j) two or more waterbreaks in a state of malfunction, if waterbrake equipment is provided
k) interruption of primary navigational positioning system, unless a redundant system is provided
l) failure of gun timing controller
m) over-driving or clipping of any trace
n) loss of raw navigation data being permanently recorded

2.6.6 Monitor Records for Digital System

Multi-channel paper monitors will be made at every 40th shot, or as required to display all traces and systematically annotated as produced.

Oscillograph camera will be optically aligned and photography will produce permanent records with appropriate contrast.

Timebreak, recording system time base and 100 Hz cross-reference signal from the cameral timing line generator, 10 ms timing lines, record number, and all seismic detector groups will be displayed.

Timing reference and timing line signals will coincide within limits of 0.002 seconds on a 2 second monitor record.

Monitor records will be annotated such that traces are not ambiguous.

2.6.7 Polarity

Polarity convention will be in accordance with the SEG Committee on Technical Standards recommendations, such that compressional waves produce negative voltages which are recorded as negative numbers on magnetic tape, and deflect galvanometers downward to produce wavelet minimal (white) troughs on monitors.

All seismic channels will be recorded and processed with identical polarity.

Polarity will be checked by tap test prior to commencing survey and will be documented on hard copy at start of survey, and again whenever sections of streamer are replaced, or whenever there are permanent electrical disconnections, or whenever any change in signal routing is made.

Polarity corrections will be made when necessary at the point of reversal, such that identical polarity exists at all test points coupled between hydrophones and magnetic recording heads.

2.6.8 Tape Transports (if used)

Tape transport skew, both static and dynamic, will be within manufacturer's specifications for sample rate, bit packing density, and recording speed.

Tape speed will be maintained within 1% of manufacturer's specifications. Tape heads will be cleaned between each production tape prior to loading.

2.6.9 Recording Media

All seismic data will be recorded on new and certified media.

Each medium will contain the following information on permanent labels:

a) project designation
b) line number and shot point sequence
c) format, bit packing density, and sample rate
d) a boat name and number
e) direction of traverse
f) date

2.6.10 Seismic Sensor Acquisition Not To Commence

Recording of data from an individual sensor will not commence on any line when the following conditions occur:

a) existence of any conditions described in section 2.6.7
b) one or more units of the source array or its sensor are malfunctioning
c) more than 2 of 24 traces, or 2 adjacent traces, or any one of the near 4 are defective as defined in section 2.6.2
d) if more than one cable depth transducer is inoperative
e) polarity is not within specification
f) multi-channel monitor camera is inoperable
g) single channel section plotter not functioning
h) primary navigational positioning system malfunctioning
i) streamer noise exceeds limits defined in section 2.6.1
j) gun string depths vary by more than plus or minus 1.0 m
k) streamer depth exceeds 1.0 m from specified operating depth
l) air pressure falls below 1850 psi from a normal 2000 psi operating pressure

2.6.11 Seismic Sensor Data Acquisition Not To Continue

Acceptable data recording will not continue for a specified sensor if the following conditions occur:

a) cable noise exceeds specification
b) 1 or more traces in a 24 trace system, or 2 adjacent traces, or any 2 traces among the near 6 traces are defective as defined in section 2.6.2
c) more than one streamer depth detector is inoperative
d) streamer depth varies ore than plus or minus 1.0 m from specified operating depth, or more than 1.0 m between adjacent depth transducers
e) or more successive misfires, or more than 25 misfires during any 120 seismic shots
f) misfire rate exceeding 5% on any line
g) malfunction of any non-redundant unit of the source array or its sensors for more than 10% of any line, or variation in depth of source by more than plus or minus 1.0 m
h) air pressure falls below 1900 psi from normal 2000 psi
i) primary navigation system malfunctioning, or calibration not verified
j) single trace, monitor camera, data logger, or extended header printout fail for more than one hour
k) off-line variation is greater than 100 m except when avoiding obstruction

2.6.12 Reshooting

Reshooting will be carried out in such a manner that a full fold stack of data acquired within the specifications of this document will be gathered on a continuous basis.

2.6.13 Documentation and Reports

Recorded production and test data will be identified such that no ambiguity can exist. Each monitor record will be stamped, or any appropriate alternative method containing the following information:

a) date, line and shot number, and channels displayed
b) reel and file numbers
c) misfires, cable or group malfunctions, instrument troubles, missed time breaks
d) possible sources of unwanted energy, position of other boats in the area with respect to the cable, or other phenomena which could affect the data quality
e) trace numbering convention used, including description of auxiliary traces, if necessary

f) Observers will keep neat and legible logs showing:

g) position of energy source with respect to the boat and hydrophone group nearest the vessel on each line, and highlighted when changes are made

h) date, time of each shot, area identification, and line numbers

i) source and detector depths

j) reel, file and shot point numbers

k) recording system fixed parameters

l) position of all variable control settings

m) adequate description of all unusual circumstances surrounding any change affecting data quality

2.6.14 Recording Instrument Specifications

The system will conform to manufacturer's published specifications, except that system noise at maximum gain will be no more than 1.5 microvolts RMS, crossfeed separation shall be greater than 80 dB at fixed gain, AC gain step accuracy will be 0.025% step-to-step gain, and harmonic distortion shall not exceed 0.0%.

Appropriate technical manuals along with schematics shall be maintained on board for all equipment used. Instrument test schedules and procedures shall adhere to manufacturer's recommendations and industry standards. The quality control supervisor may change test schedules as needed.

Digital/multiplexed streamer systems shall be capable of efficiently producing daily, weekly, and monthly tests to determine dynamic range, pulse test, harmonic distortion, gain accuracy, crossfeed, system equivalent input noise, gain linearity, header recording quality, and tape skew.

2.7 Data Concerning The Top 100 Meters Below The Seafloor

If the bandwidth of the MCS system does not allow recording of frequencies up to several kHz then an independent system should be used to evaluate the shallow geology (see section 2.5.1).

Shallow geology at the site can be assessed using, for example, a sub tow boomer acoustic source, single channel receiver and graphic recorder (or approved equivalents). Example instrument specifications and settings are set out below:

Source

Type: ....EG&G Sub Tow Boomer
Power Supply: ....EG&G 231/232
Transducer/Source Depth: .... 3 m
Hydrophone: .... Integral

Recording Unit **Make/Model**

Graphic Display: .... EPC 3200s
Fire Control: .... Gardline FCU
Time Variable Gain: .... TSS 307
Band Pass Filter: .... Krohn-hite 3500
Swell Filter: .... TSS 305

Operating Parameters

Energy/pulse: .... 300 J
Firing Cycle .... 375 ms
Recorder Sweep: .... 125 ms
Timing Lines: .... 12.5 ms
Print Delay: .... 150 ms
Band Pass Filter: .... 1-6 kHz

Table 1 presents characteristics of a number of other potentially acceptable single channel analog system sources.

	Fundamental frequency	Bandwidth	Resolution (m)	Penetration (m)
Huntec Deep Tow Boomer	1.5-3.5 kHz	0.2-5.5 kHz	0.2	15-80
Pingers	3.5 kHz	1.4-4.5 kHz	0.6	5-40
1 kJ sparker (multi-tip)	0.8 kHz	0.2-2.0 kHz	2.0	100-150
Mini sleeve exploder	250 Hz	60-1000 Hz	1.5	800-1000
13 kJ sparker (9 tip)	100 Hz	40-300 kHz	2.5	1000-1200
Airgun array (4 x 40 cu. in)	80 Hz	10-200 Hz	4.0	1500-2500

Table 1. Characteristics of commonly used seismic sources.

A seismic velocity of 1600 meters per second is assumed in converting travel times to depths, in view of the generally soft nature of the superficial sediments. In most circumstances, this figure is likely to be within 5 % of the true value. Laterally, plotting accuracy is affected by errors of towing offset, of the positioning system and of the limitations of a omnidirectional source. Moreover, geological complexity, reflector depth and survey line spacing all affect accuracy and in ways which are not easily predictable. As a broad guide, practical limits on this survey are estimated at 0.2 meter to 10 meters depth and 0.5 meter for reading accuracy, 0.5 to 1 meter for contour interval and 10 meters for plotting accuracy.

Analog subbottom seismic reflection profilers: Subbottom reflection profiles shall be acquired in a manner that will allow optimum detection and resolution of subsurface anomalies and structural information within two target depth intervals of 0.05 (shallow) and 1.0 (medium) seconds, two-way travel time. The subbottom profiling systems should be complementary; no gaps should be present over the entire 1.0 second interval of data required. The subbottom profiler should employ a rapid-firing, single or multiple frequency source/receiver system centered within a range of 0.8-20 kHz (e.g. tuned transducer, boomer, sparker). A 19-inch, dry paper, flatbed recorder shall be used to record a continuous analog display of subbottom information to 0.05 seconds (minimum), two-way travel time. Alternative data acquisition systems and strategies will be considered, with approval by the Science Operator.

2.8 Interpretation

It is important that all the data relating to gas hazards at a proposed site be evaluated by an independent authority in gas hazards. This authority could be an individual, a small group of experts, or a company. Selection of this authority will be made by the Science Operator.

2.9 Magnetometer

Magnetic data are not required for detecting shallow gas hazards, but may be helpful in locating man made iron objects if they exist. If there is reason to think that man made hazards exist a magnetometer survey may be specified by the science operator. If it is then the instrument should be sufficiently sensitive to resolve unambiguously at least a two gamma anomaly with respect to background intensities. To optimize target resolution, the sensor should be towed at a constant height above and as close to the seafloor as possible in a manner consistent with overall survey strategy. If used, an operator's log listing survey parameters (i.e., tow height, vessel speed, cable length out) will be maintained.

3. Drilling Procedures in Shallow Water

By: Dave Huey, Supr. of Development Engineering, ODP-TAMU and Ron Grout, Supr. of Drilling Operations, ODP-TAMU

Problem Definition and Assumptions

The problem is defined as one of assuring ship and personnel safety if ODP drilling operations are to be conducted in shallow water areas where the existence of hazardous amounts of shallow gas are deemed to be geologically possible, i.e. sedimented continental margins, but not coral atolls or shallow mid-ocean ridges, etc.

The situations of interest break down into three general cases:

Case 1: Water depths greater than 200 m

Only existing ODP safety preparations and precautions would apply to any site to be drilled in water depths greater than 200 m which passed PPSP review. It is assumed in this case that inadvertent release of shallow gas would not present an abnormal safety hazard to the ship or crew since the possibility of a dangerous surface gas "boil" or flammable gas at the sea surface would be effectively mitigated by the 200 m-plus water column.

Case 2: Water depths less than 200 m, and seafloor penetration less than 1000 m bsf

Special technological requirements to allow drilling such sites include:

a) sonar monitoring of the borehole at the seafloor for earliest possible detection of released gas bubbles, and,

b) an emergency pipe release capability to allow rapid drive off even if the pipe is stuck in the hole or there is thought to be insufficient time to safely retrieve the drill string.

The assumptions made in this case are that the site could only be accepted for drilling if a tightly specified seismic survey processed specifically to identify shallow gas pockets had been done and no gas hazards were identified. Such surveys are expected to be unreliable to identify gas hazards at depths greater than 1000 m subsurface.

However, because of the unpredictable nature of shallow gas, prudence dictates that the two precautions above be available as a final safety measure for protection of the ship as drilling proceeds.

Case 3: Water depths less than 200 m, and seafloor penetration greater than 1000 m bsf

Special requirements to allow drilling at such sites include items 1) & 2) above, plus:

3) adequate BOP/well control measures to contain and kill any type of hydrocarbon kick if previously undetected pressures are encountered at penetration depths greater than 1000 m bsf.

The inclusion of full well control capability implies that conventional oilfield casing and seal systems will be used and that adequate casing, cementing, sealing, and pressure testing steps will be taken in the installation of the casing, BOP and riser to guarantee pressure containment in the event of a kick.

Technology Assessment

Sonar monitoring of the borehole at the seafloor

The Mesotech sonar used for reentry work is deemed suitable by the manufacturers as a gas bubble detector tool. The frequency (675 kHz) is within the range of the recommended frequencies for gas bubble detection. Gas bubbles make very good sonar targets and are expected to be detectable even in murky water where TV monitoring would fail. Resolution of the system would be limited to individual bubbles about 1.5-2 inches diameter or smaller bubbles making a cluster at least that size. This resolution limit is controlled by video presentation (pixel density), rise time of the transducer, and angular resolution of the transducer assuming a target distance of about 10 m.

Delivery of the sonar to the seafloor and aiming it at the "wellhead" could be accomplished by mounting the sonar on a pan and tilt mechanism and attaching to the clump weight of the taut wire. This would require either a second conductive line in the water with the taut wire or restringing the taut wire system with a suitable E-M cable. A simpler approach might be to hang the clump weight with the sonar over the side from a crane boom and string the wire to the sonar in a slack form suspended by a buoy in a manner similar to the deployment of water guns for VSP experiments. Either method could probably be worked out with minimal cost and difficulty.

Additionally sonar monitoring stations would have to be set up and monitored 24 hours a day if this early detection system was to have any real value.

It would also be advisable to do regular local current profiles at shallow water sites. Updated information on current directions would dictate the best choice of direction for driving off the ship if rapid abandonment was necessary.

Emergency Pipe Release Capability

Although a number of techniques to achieve emergency pipe release can be conceived the most attractive would be to acquire an off-the-shelf double shear ram BOP unit complete with a hydraulic accumulator unit from a rental company. The accumulator system would be sized to allow only two or three shear operations expected to be necessary in an emergency release situation. It would be necessary to modify the upper guidehorn to allow for mounting the BOP module in the guidehorn with the hydraulic accumulator system located on the main deck in the moonpool area. Modifications for mounting in line with the upper guidehorn are estimated at $25,000.

A typical BOP module and accumulator unit is available off-the-shelf from Petco/Weatherford for $2530/day rental. Thus the costs for one leg for this equipment would be about $215,000. It is reasonable to suggest that, given adequate advance preparation time, an alternative approach could be pursued by locating a salvage BOP/shear ram assembly plus accumulator system and modifying them specifically for ODP requirements at a one time cost of, perhaps, $50-60,000.

Well Control - BOP - Riser

The question of achieving well control capability for the ship when drilling in water depths less than 200 m has occasionally been posed as if the shallow water (shallow by ODP standards) might present a low-cost approach not achievable for riser drilling as envisioned for more normal ODP sites. Unfortunately, this concept cannot be substantiated.

Shallow water riser drilling (less than 200 m) would require only a handful of riser joints without buoyancy systems. The storage area required for the joints would not be significant.

However, this is virtually the only benefit to be expected in shallow water. In every other detail, well control capabilities would require the same equipment and shipboard modifications described in past riser drilling analyses: risers tensioners, BOP, rig floor BOP storage and deployment features, Koomey (or other) BOP control system, mud return and solids separator systems, mud logger system, etc. There is no "short-cut" system that can be expected to provide adequate well control capabilities to contain and allow remedial action necessary to kill a gas kick. Furthermore, if some novel, "poor boy" well control system could be invented for ODP's special requirements in these cases, it is highly unlikely that offshore oil and gas regulatory bodies would grant approval for use of such a system within their jurisdictions. Any such request might, in fact, backfire and cause such an agency to take a closer look at ODP drilling operations within their waters, resulting in undesirable new regulations for ALL ODP drilling planned in those areas.

Full well control capability would also require control over preferential release of downhole pressures up the drill string while conducting wireline coring operations. An additional backflow preventer would have to be integrated into the drill string to contain pressure during those instances when a core barrel is in place holding open the standard (or LFV) float valve and the pipe is open ended at the top, e.g. when stabbing the sinker bars to go after a core barrel. This requirement is not difficult. If off-the-shelf equipment is not available that mates with ODP wireline core barrels, a variation of the LFV could be developed at minimal cost which could be expected to serve the purpose.

Estimating the cost and shipboard space impact for any switch to riser/BOP drilling capabilities has already been done during the Riser Workshop in April 1987. Similar analysis work would be done in pursuit of the Deep Drilling RFP currently in the hands of several prospective vendors. Application to shallow water/shallow gas objectives would follow similar requirements except for the length of the riser and the load rating of the riser tensioners. Each of these studies, even in their most preliminary stages, suggests that major and expensive changes to the current shipboard configuration would be required. Space for the science laboratories would certainly be impacted.

4. Conclusions

The main conclusions from this meeting were:

1. Open-hole drilling in shallow water is reasonably safe if proper hazards surveys are conducted and combined with proper data processing and interpretation.
2. Hazards Surveys must be a requirement for ODP drilling on sedimented shelves in water depths of 200 m or less.
3. Sub-bottom penetrations at those depths, without BOP and mud-weight capabilities, must be limited to 1000 m.
4. Operational procedures for shallow water drilling such as: dropping the drill string, monitoring the seabed for gas escape, and safety contingency plans must be developed.
5. Interpretation of the survey data in terms of shallow gas hazards should be made by experts in the field who are also not associated with the scientific proposals justifying the program.
6. ODP's slim, open-hole drilling from a dynamically positioned vessel is a relatively safe method for shallow water operations but blowouts must be avoided.

References

Judd A.G. and M. Hovland, 1992. The evidence for shallow gas in marine sediments, *Continental Shelf Research*, vol. 12, no. 10, pp 1081-1095.

Brown, A. R., 1988. Interpretation of three-dimensional seismic data, *AAPG Memoir* 42, 253 p, American Association of Petroleum Geologists, Tulsa, Okla., U.S.A.

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Special Issue No. 3: Initial Site Prospectus, Supplement Two, June 1980 (Vol. VI)
Special Issue No. 4: Guide to the Ocean Drilling Program, September 1985 (Vol. XI)
Special Issue No. 4: Guide to the Ocean Drilling Program, Suppl. One, June 1986 (Vol. XII)
Special Issue No. 5: Guidelines for Pollution Prevention and Safety, March 1986 (Vol. XII)
Special Issue No. 6: Guide to the Ocean Drilling Program, December 1988 (Vol. XIV)
Special Issue No. 7: Ocean Drilling Program Guidelines for Pollution Prevention and Safety, Oct., 1992 (Vol. 18)
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JOIDES Resolution Operations Schedule

Leg	Destination	Cruise Dates *	In Port †	Total days	Transit	On Site
157	VICAP/MAP	July 29- September 23, 1994	Barbados, July 24 - 28, 1994	56	12	44
158	TAG	September 28- November 23, 1994	Las Palmas, September 23-27, 1994	56	13	43
	Transit to drydock	November 24 - November 30, 1994	Las Palmas November 23, 1994	6		
	Drydock at Falmouth, England					
	Transit to Dakar	December 24, 1994 - January 3, 1995	Falmouth	9		
159	Eq. Atlantic Transform	January 5 - March 2, 1995	Dakar January 3-4, 1995	56	13	43
160	Mediterranean I	March 7 - May 2, 1995	Las Palmas March 2-6, 1995	56	15	41
161	Mediterranean II	May 7 - July 2, 1995	Napoli May 2-6, 1995	56	11	45
162	Atlantic Arctic Gateways II	July 7 - September 1, 1995	Leith July 2-6, 1995	56	15	41
163	Gas Hydrates	September 6 - November 1, 1995	Reykjavik September 1-5, 1995	56	13	43
164	DCS Engineering	November 6, 1995 - January 1, 1996	Miami November 1-5, 1995	56		

† Although 5 day port calls are generally scheduled, the ship sails when ready.

JOIDES Meeting Schedule

Date	Place	Panel
September 21-23, 1994	Palisades, NY	DMP
September 25-27, 1994	Las Palmas, the Canaries	SMP
September 27-29, 1994	Townsville, Australia	OHP
October 3-5, 1994	Rouyn-Noranda, Québec, Canada	LITHP
October 11-14, 1994	Fukuoka, Japan	SGPP
October 13-14, 1994	Stavanger, Norway	PPSP
October 20-22, 1994	Cyprus	TECP
November 7-8, 1994	College Station, TX	TEDCOM
* November 14-16, 1994	Palisades, NY	SSP
November 28, 1994	College Station, TX	DRILOPTS
November 29, 1994	College Station, TX	PANCH
Nov. 30 - December 3, 1994	College Station, TX	PCOM
January 30- February 1, 1995	Hawaii	EXCOM
* March 2-4, 1995	Miami, FL (FIU)	OHP
* March, 1995	Boulder, CO	SGPP
* Spring, 1995	United Kingdom	DMP
* Spring, 1995	San Luis Obispo, CA	TECP

* Meeting not yet formally requested and approved