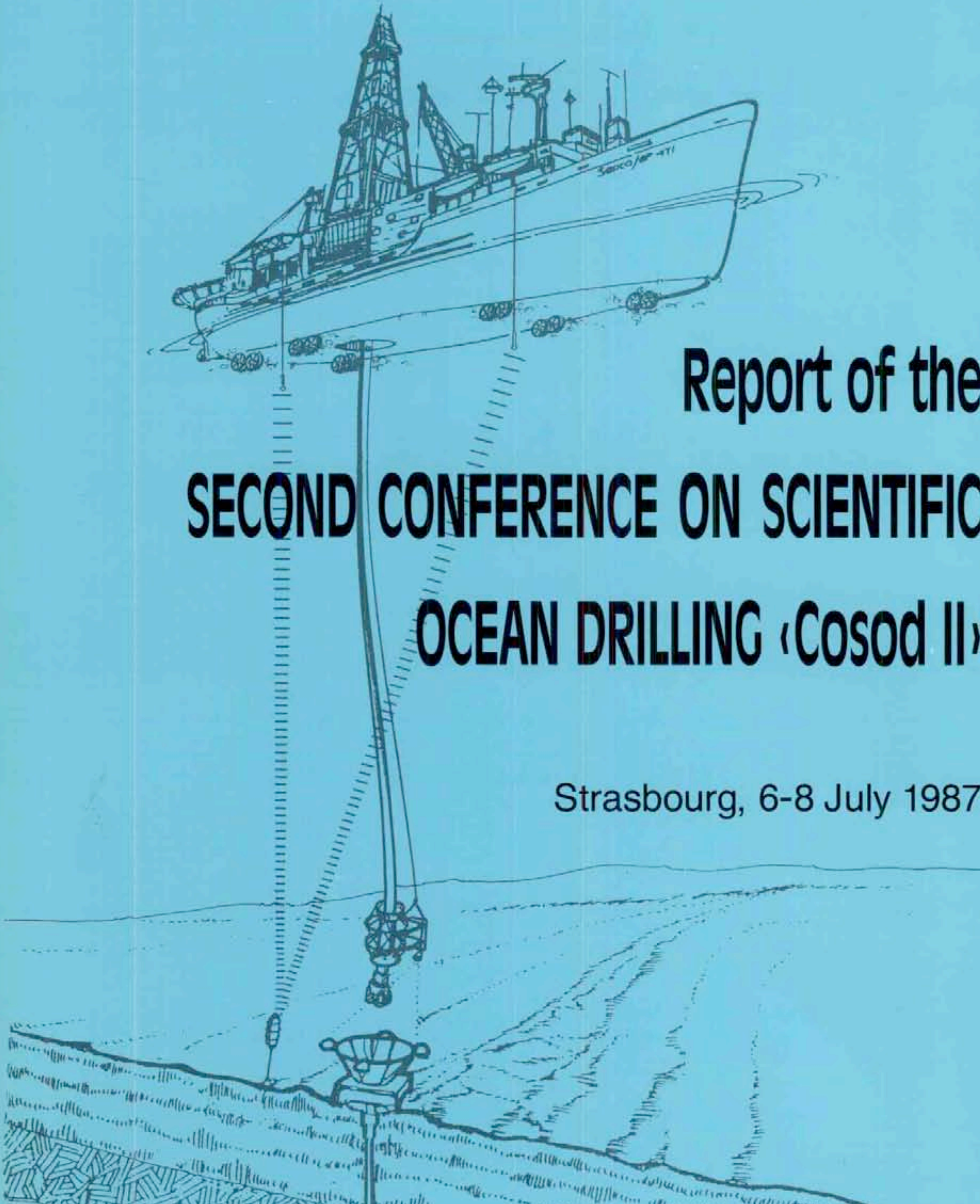

Report of the SECOND CONFERENCE ON SCIENTIFIC OCEAN DRILLING ‹Cosod II›

Strasbourg, 6-8 July 1987

JOINT OCEANOGRAPHIC INSTITUTIONS FOR DEEP EARTH SAMPLING

EUROPEAN SCIENCE FOUNDATION

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TABLE OF CONTENTS

PREFACE

The Second Conference on Scientific Ocean Drilling (COSOD II) was initiated by the Executive Committee of JOIDES (Joint Oceanographic Institutions for Deep Earth Sampling). "The prime objective of COSOD II", as defined by the Planning Committee of JOIDES, was "to make recommendations for future scientific and technological objectives for the Ocean Drilling Program, bearing in mind the scientific and technical progress of the ODP (Ocean Drilling Program) to date. As part of this charge, special attention should be given to the development of scientific programs within the ODP." Thus, the mandate of the conference in Strasbourg was not to draft a detailed drilling plan for the 1990's but to identify the most significant problems within the Earth sciences to which scientific drilling might contribute solutions.

The preparation for COSOD II was entrusted to a Steering Committee of twelve members who met in Strasbourg from September 30 to October 2, 1986. The Committee decided that the best format for the Conference would consist of five parallel workshops, each run as a Penrose-type conference. The workshops were established along thematic lines. The choice of thematic rather than disciplinary workshops was made to focus on scientific problems which were sufficiently broad to interest the world scientific community.

The Steering Committee established five working groups corresponding to the five workshops. Each working group prepared a position paper which was discussed during the Conference. Technological white papers had been prepared before the Conference and provided to the thematic working groups.

The Conference was hosted in Strasbourg, France, by the European Science Foundation on July 6 to 8, 1987 and was attended by 340 scientists from 20 countries. The Steering Committee met with the Working Group Chairmen the day after the Conference to discuss the main conclusions. Then the working groups redrafted their position papers to incorporate the conclusions of the discussion in Strasbourg. Finally, the Steering Committee met in Paris with the Working Group Chairmen from October 19 to 20 to draft the final recommendations.

The report consists of three parts : the recommendations of the Steering Committee, the five working groups' position papers, and three technological white papers.

XAVIER LE PICHON
Chairman, COSOD II Steering Committee

RECOMMENDATIONS OF THE STEERING COMMITTEE FOLLOWING THE SECOND CONFERENCE ON SCIENTIFIC OCEAN DRILLING (COSOD II)

INTRODUCTION AND GENERAL RECOMMENDATIONS

The Earth is a complex interactive system in which the biosphere, the atmosphere, the ocean, the crust and the mantle are closely linked. It has become increasingly apparent that we need to understand how the evolution of this system progressively modifies the environment in which we live. The oceans cover two thirds of the surface of the Earth and contain far more than two thirds of the information necessary to reconstruct the dynamics of this system.

This global perspective dominates the conceptual framework which emerged from the COSOD II Conference and led its participants to propose another decade of investigation, after nearly twenty years of very successful drilling. New frontier experiments, many of which require innovations in technology, are proposed to obtain a much better understanding of the dynamics of the Earth system. Most of these experiments are designed to test global models. Although global model testing already characterized the early drilling in the late sixties, which so successfully tested the plate tectonic model, it is far more pervasive in the recommendations made in this report and now extends to climate, sealevel, biological evolution, fluid and solid Earth circulations, stress distribution and plate dynamics studies.

The experiments proposed are of four main types. Global arrays of holes would be drilled into the sedimentary layers to determine the response of climate, of sealevel and of biological evolution to variations in the Earth's orbit, to catastrophic extraterrestrial encounters and major volcanic episodes or to the slow but inexorable movement of the plates. The sampling arrays would be located with great care to identify the different signals coming from the controlling forces as a function of time, space and past depth.

Global arrays of holes through the igneous basement would be drilled to measure the distribution of stress in the oceanic plates and relate the stress patterns to the driving forces, to establish deep sea geophysical observatories for global seismic monitoring, and finally to map the chemistry of the ocean crust and relate it to the dynamics of the mantle.

Deep crustal penetration into the lower crust would be attempted to understand the dynamics of the solid and fluid circulation into and out of the mantle. Deep crustal penetration is also required to test the exciting new models of formation of passive margins.

Arrays of permanently instrumented holes along active boundaries would be used as natural laboratories to monitor the flow of fluids that deeply affects the tectonics of the plates and the global oceanic budget. Such natural laboratories might make a significant contribution to seismicity studies by establishing a link between fluid flow and earthquakes.

The importance of siting the drill holes in the appropriate geological context cannot be over-emphasized. The regional context must always be known sufficiently precisely so that representative site selection is possible. In addition, some of the programs proposed consider drilling as one component of a broader experiment.

Although this report does not outline a detailed ten-year drilling plan, which would be premature, we have checked that the main objectives proposed can be reached over a decade of drilling with a budget about 10% to 50% larger than the present budget. The lower estimate corresponds to the minimum estimated increase necessary to meet the technological development needs without which a large part of the program proposed would not be feasible. The COSOD II Conference revealed a clear consensus that the present program has been severely compromised by insufficient investment in technology. The higher estimate includes the possibility to lease temporarily alternate drilling platforms to implement specific drilling programs rapidly and efficiently. This will introduce some very needed flexibility in the programming.

A program which addresses a global Earth system requires truly international cooperation. We advocate such collaboration both in the scientific and technological domains. In particular, we recommend to study the possibility that different countries, or groups of countries, contribute the alternate drilling platforms or the needed technological innovations which were mentioned above.

Finally, the COSOD II Conference also revealed a great concern among the scientists that the present planning and advisory structure of the Ocean Drilling Program (ODP) is not adequate to give the long-range continuity necessary for the experimental approach of the programs proposed and does not give the possibility of sufficient participation to the scientific community at large. We recommend that fundamental changes be made in the planning and advisory structure to meet these requirements.

CONCEPTUAL FRAMEWORKS OF THE PROGRAMS PROPOSED

The programs proposed have been prepared by five different working groups and have been discussed in corresponding workshops at the Conference, each dealing with a major theme chosen by the Steering Committee. Here, we briefly summarize the conceptual frameworks of these five programs. The complete position papers are printed in the following chapters.

Changes in the Global Environment

The Earth's climate has shown through geological time an extreme variability which involves changes in the atmospheric composition and wind-field ; in the chemical composition, density structure, and circulation of the surface and deep ocean ; in continental morphology ; in the distribution and volume of ice ; and finally in sealevel.

Our strategy of research is based on the concept that the climatic changes we observe fall into two main categories with two distinct frequency bands. Tectonically driven trends, oscillations and steps occur on time-scales of a few million years or more. They correspond to changes in the climatic mode that are associated with major differences in sealevel, thermal regimes, global pattern of winds, in the chemical balances of important elements such as carbon, and in the three-dimensional patterns of ocean circulation. Oscillations driven by changes in the orbit of the Earth, on the other hand, appear on time-scales of 20 000 to 400 000 years wherever the sampling density is adequate. They reflect changes in the seasonal and latitudinal distribution of incoming solar radiation. In addition, there are changes brought about by biological evolution.

The sensitivity of the system's response at the higher frequencies differs from one climatic mode to another, as evidenced by changes in the amplitude and frequency of the orbitally driven signals. The physics of radiation which causes the forcing in each orbital frequency band is known quantitatively, and general circulation models of the atmosphere and ocean give us quantitative insights into the response of the system to external forcing. There is thus an opportunity to formulate and test quantitative models of the mechanisms of climate change in different frequency bands. This experimental approach to historical climatology should reveal how the global climate system operates. It should also help to determine how sensitive this global system is to perturbations in its boundary conditions, whether those perturbations are natural or man-made.

Mantle-Crust Interactions

The development of plate tectonic theory coupled with advances in the understanding of mantle convection has led to the realization that the solid Earth is a system in active circulation. This circulation includes not only the movement of the plates, but also intricate exchange between ocean crust and seawater through hydrothermal, sedimentary and biologic activity, recycling of material from the Earth's surface to the mantle with subduction of the lithosphere and redistribution in the mantle's interior through convection. Through time this circulation has created the continents and given the mantle its heterogeneous physical properties and chemical composition. The term "geochemical cycles" is now as apt for solid Earth circulation as it is for surface circulation, and entails the same close connection between chemical fluxes and physical properties. In terms of this conceptual framework, a thematic priority is to understand as quantitatively as possible the present systematics of this solid Earth circulation system, and the record of its action through time.

Efforts must be made to quantify the geochemical fluxes that occur as a result of plate circulation. In many cases, critical questions regarding the fluxes cannot be answered without deep crustal penetration. An ultimate objective in this regard is the capability of measuring total crustal sections, and this remains a long-term goal to be achieved. The processes that control the fluxes also need to be studied, both because of their intrinsic importance and because only by understanding these processes can a small number of deep penetration holes be sufficiently informative. Drilling plays an important role in such studies, but needs to be placed in the context of intensive studies using other approaches.

The time-integrated results of circulation of the solid Earth are expressed in the composition and structure of the mantle. In analogy with sea floor magnetic anomalies that carry a record of the Earth's magnetic history, the basaltic ocean crust carries a record of mantle composition and how it is organized, and in certain cases may directly reveal mantle kinematics. Systematic mapping of crustal composition would provide new constraints on mantle composition, and is a prerequisite on the testing and evaluation of physical models of mantle convection.

Fluid Circulation in the Crust and the Global Geochemical Budget

The circulation of seawater through the ocean crust is one of the Earth's major exchange processes. Cooling the oceanic lithosphere and transferring elements between the ocean and the crust, it provides a mechanism whereby changes in the Earth that affect oceanic lithosphere are relayed to the hydrosphere and thence to the atmosphere, with consequent effects upon the biosphere. Hydrothermal circulation, driven by forced convection at mid-ocean ridge axes and by free convection at ridge flanks, alters the ocean crust and influences the distribution in the Earth of elements such as carbon.

Circulation through the crestal areas of the mid-ocean ridges is the most vigorous, with fluid temperatures in excess of 350°C. However, the influence upon the global geochemical budget of circulation through the cooler but much larger area of the ridge flanks may be just as great, because the total flux there is about twenty times greater.

At subduction zones, the igneous ocean crust and the overlying wedges of accreted sediments lose water back into the ocean from dehydration reactions and through the expulsion of porewater by tectonic compaction. The very high pore fluid pressures that are generated within these wedges control the evolution of their growth and deformation. They also probably control the partitioning of the oceanic sedimentary layer into a lower subducted layer and an upper layer accreted to the wedge.

Continental margins appear to host large gravitationally driven circulation systems of meteoric ground water and saline fluids produced by the formation of evaporites or by leaching of evaporitic rocks.

We have the opportunity to determine the fundamental elements of the fluid circulation and of the chemical and energy flux between the oceans and the oceanic lithosphere, provided a long-term commitment to the development of the required new technology is made.

Stress and Deformation of the Lithosphere

A primary element in our understanding of the dynamics of the Earth is a definition of the present state of stress in the oceanic lithosphere. This information can be inferred from seismicity and has been measured directly in many places on the continents, but there are few constraints from the ocean basins. Comprehensive mapping of the state of stress in the ocean basins of the world could be used to test physical models about the forces which drive and deform plates.

We also propose that several crustal holes be used as seismic observatories. Recent major advances have been made in improving upon radially symmetric models of the Earth's interior, both in the core and mantle. These results provide fundamental information about the driving mechanisms of plate tectonics. The resolution of tomographic imaging of the Earth's interior, however, is severely limited by lack of seismological data from the ocean basins.

Finally, we have identified objectives at the margins of oceanic plates where the dynamics of these important tectonic environments are poorly understood. In particular, conjugate passive continental margins would have to be drilled deep into the crust to test the thermal and structural predictions of competing models of pure and simple shear during the early period of rifting and continental break-up.

Evolutionary Processes in Oceanic Communities

Many conceptual models in evolutionary paleobiology recently put forward can be applied to and tested with the complete deep-sea microfossil record. The chronologic resolution of bio-stratigraphic, magneto-stratigraphic, chemo-stratigraphic and isotope-stratigraphic techniques is now such that evolutionary processes can be detected on the time-scales on which they operate. Hydraulic piston coring techniques are capable of providing a complete recovery of the stratigraphic record from most areas of the biogeographic realm of oceanic microfossil groups.

Only few such high quality sections are now available for a study. Their number, their geographic distribution and the stratigraphic coverage need to be improved substantially to establish the major patterns in a quantitative way and determine the feed-back mechanisms between change in global environment and the biosphere. Although evolutionary paleobiology of microfossils is still a nascent discipline, it is the most promising source of data to evaluate the history of global change in the geosphere and the biosphere.

We have identified three specific drilling targets to study important evolutionary processes. First, a global array of well preserved and completely recovered Neogene sediment sections would form the basis of morphometric analyses to test models for patterns and modes of evolution. They would also serve to analyse feedback mechanisms between the atmosphere and ocean and the biosphere.

Second, the study of the effects of environmental catastrophes, such as the terminal Cretaceous event, upon the biosphere-geosphere system will give information on the boundary conditions for life on Earth. How and on what time-scales are the habitability of the oceans and the Earth at large restored ? We propose to obtain relatively few complete records from various water depths and areas for that purpose.

Third, long-term forcing of the global chemical budget and climate by biotic evolution is recorded in the oceans' sediments, as evidenced by the successive rise to dominance of various calcareous and siliceous plankton groups since the Late Jurassic, one hundred and forty million years ago. There are only a few places where a well preserved Jurassic and younger Mesozoic section can be obtained. Yet, if we could quantify at this large scale, for the various microfossil groups, the changes in abundance, the fluxes of biogenic compounds and the taxonomic diversity, we would have the data to model the feedback mechanisms between the biosphere and the geosphere.

ILLUSTRATIVE EXPERIMENTS

To illustrate the approach we recommend, we have selected five major experiments that we consider to be excellent examples of the types of programs we propose. Significant progress could be made for each of these with about one year of drilling. These illustrative experiments are described below.

Amplitude and Timing of Changes of Global Sealevel during the Cenozoic

Global sealevels are known to vary markedly during the Cenozoic in response to plate tectonics which alter the volume of the ocean basins on time-scales longer than one million years, and to climatic influences which change the volume of water stored as ice on time scales of 20 000 to 400 000 years. But for much of the Cenozoic, the amplitudes and timing of eustatic sealevel fluctuations are not known. Our strategy for determining sealevel history is to compare sealevel estimates made by three independent approaches, using specially designed drilling arrays.

Stacking of three different estimates is necessary because each approach has its limitations and advantages. The atoll approach, based on recent developments in the stable-isotopic correlation of carbonate sequences, uses the stratigraphic record of atôll carbonates as dipsticks in regions having a subsidence history that is simple enough to be predicted with useful accuracy. Although this strategy yields discontinuous records with variable resolution, it appears to offer the best chance of obtaining reliable, quantitative, low-frequency (smaller than two million years) information on the amplitude of Tertiary eustatic sealevel variations.

The passive margin approach derives an estimate of global sealevel from stratigraphic information coded as a coastal onlap and offlap pattern on different continental margins, and the untested assumption that eustatic level estimates can be derived from these data on relative sealevels.

The isotopic approach infers changes in global ice volume from the isotopic composition of oceanic microfossils. Although this strategy can provide continuous information at periods as short as ten thousand years, its reliability depends strongly upon the accuracy of assumptions about water temperature and the isotopic composition of glacial ice.

Each of these approaches involves certain assumptions and has stratigraphic limitations with respect to range and resolution. But because the assumptions and limitations differ among the three approaches, it should in principle be possible to constrain our knowledge of eustatic changes by comparing sealevel estimates derived by the three methods for the same stratigraphic interval. Once this objective is achieved, it should then be possible to interpret apparent discrepancies among the estimates in ways that will significantly advance other aspects of our knowledge of Earth's history.

Deep Crustal Section

Ophiolitic complexes have provided a basis for models of the oceanic crust. But these models are still controversial and need rigorous testing as the great variety of ophiolites that exist need to be calibrated in terms of types of oceanic crust. They are not affected any more by the complex tectonic, thermal, hydrologic and chemical processes which characterize the evolution of an oceanic crust throughout its life cycle from the ridge crest to the subduction zone. A complete crustal section of a "live" crust is essential to test models of evolution and to constrain the global flux pattern from mantle to crust back into the mantle.

As a first step in this direction, we propose to drill a 3 km deep hole which would penetrate into the top of layer 3 as well as a similar depth hole in a nearby zone of tectonic exposure of the lower crust. This composite crustal section would be used to calibrate remote geophysical and geochemical techniques in order to rapidly investigate the crust in many other regions.

Substantial technological innovations in deep drilling will be necessary to meet this target. We believe however that, with the level of investment in technological development we propose, it will become possible to drill 3 km deep holes in the oceanic crust within a few years. Meeting this technological challenge will lead to greatly improved drilling of shallower sites and more efficient use of drilling resources. By the end of the decade, this effort would lead to the possibility to obtain a complete crustal section through a single hole, a formidable technological challenge, but one which would provide us with a fundamental yardstick through which a great variety of geophysical and geochemical modelling will be tested and validated.

Fluid Flow and the Cycle of Deformation and Seismicity in a Subduction Zone

We now know that large-scale fluid flow profoundly influences the evolution of accretionary complexes. The partition between subducted and accreted sediments, the regional temperature regime, the nature and extent of diagenetic processes, the redistribution of base metals and hydrocarbons all have been shown to depend in some measure from the complex fluid flow pattern. We also know that the tectonic processes within the accretionary complex are punctuated by large earthquakes which imply significant discontinuous changes in the distribution of physical properties such as stress, fluid flow and temperature over time-scales of years to tens of years. Yet, we still understand very little about the exact nature of the coupling between the tectonic and hydrological systems and its change through time, although simplified, essentially untested models have been discussed in the last few years.

Accordingly, we propose establishing a laboratory to monitor the flow and characteristics of fluids circulating within and escaping from a subduction zone and to relate them to rates of deformation and seismicity. Monitoring would be attempted through a series of permanently instrumented holes less than 1100 m deep, located both seaward of and on the accretionary complex. At a properly selected convergent margin, these holes would be able to penetrate through the accretionary prism into the subducted sediment layer, intercepting the entire lateral component of fluid flow. When technically feasible, a 3 to 4 km deep hole through the accretionary prism would allow additional monitoring well landward of the deformation front. Within the holes, active fluid flow conduits would be identified by geochemical and thermal anomalies and correlated to lithology, physical properties, structural features, and seismic images. A comprehensive logging program at all sites would be coupled with packer experiments designed to measure fluid pressure, permeability, fluid flow and state of stress. Long-term downhole recording of temperature, pore pressure, fluid flow rates, chlorinity, strain and seismicity would link fluid fluxes and deformation and help assess how much fluid flow is affected by earthquakes.

Stress Pattern within an Oceanic Plate

Within the frame of a global program of stress measurements, a first critical experiment would be to establish the stress pattern within a single oceanic plate using a few well located holes into the oceanic basement. This experiment would show if a simple plate-wide pattern of stress exists. If so, the relative importance of the forces acting to drive the plate (ridge push, slab pull, hotspot induced mantle flow, etc.) could be assessed. The plate chosen should be one in which gradual change in the stress direction is expected, and in which the directions of the ridge push, trench pull, plate drag etc. forces are not parallel to each other nor parallel to the ridge-formed "grain" of the sea floor.

The North Pacific, with the Juan de Fuca ridge and East Pacific rise, with the competing pulls of the Aleutian, Japanese and Melanesian subduction zones and with its variety of sea floor "grains", might be an appropriate choice. Space geodetic techniques appear to indicate there intra-plate stretching of several mm/yr. Knowledge of the stress directions would be needed to test and enhance the meaning of these results in terms of a plate dynamics model.

Cretaceous/Tertiary Boundary

The Cretaceous/Tertiary (K/T) boundary experiment would examine a major environmental catastrophe which has been related to extraterrestrial impacts and (or) to major volcanic eruptions. This cataclysm occurred about 65 million years ago and resulted in a uniquely rarefied global biosphere. High resolution fossil and chemical records would be collected along environmental and biogeographic gradients. The complete recovery of interbedded hard and soft lithologies would require improved drilling and coring techniques. The principal objective of the experiment would be to determine, on a global scale, the evolutionary patterns and rates before, during and after environmental disturbances which led to the disappearance of a significant mass of oceanic biota. The final goal would be to evaluate and model the interaction and feed-back mechanisms between the geosphere and the biosphere and to test quantitatively the predictions of a number of evolutionary models that have been or are being developed to explain extinction, acme layers, radiation and taxonomic diversification of marine organisms.

TECHNOLOGICAL REQUIREMENTS

In the past five years of drilling, scientific success has been severely compromised by insufficient investment in technology and the same problems would prove fatal to the new programs proposed by COSOD II. Only 3.3% ($ 1.2 M) of the total cost of the present program is devoted to developing the technology. Engineering development in ODP is seriously underfunded and understaffed. Modifications to the existing ODP system, while being able to yield useful improvements in certain drilling environments, cannot provide the answers to the major drilling challenges being faced. Major engineering development must be undertaken to fully meet many of the scientific objectives outlined in this report, as discussed at length in the three technological chapters. *We recommend that an additional $ 4 M per year be progressively added to the present level of funding in order to be able to achieve the necessary innovations in time for the drilling to take place.*

In this section, we briefly mention a few developments we consider specially important and we refer to the technology chapters for a more detailed discussion. A very important development in hard rock drilling is to be able to deeply and sufficiently rapidly penetrate fragmented and abrasive formations and to overcome problems of hole stability and poor recovery of cores. Complete recovery of all types of sediment, including alternations of hard and soft lithologies, of unconsolidated sands, clays and shales is an important requirement of many of the programs. Core orientation is another area where new developments are needed. High temperature drilling requires innovation in drilling technology as well as new logging tools and special experiments. Very high resolution logging of physical properties of sediment is necessary to determine sedimentary cyclicity. Deployment of instruments within holes for periods in excess of a year requires developments of downhole instrument packages and adequate transmission systems.

Several of the drilling targets require, or would be more efficiently drilled by other kinds of platforms than *JOIDES Resolution*. Deep penetration wells may eventually need deployment of a riser system, perhaps a slimline riser, perhaps a full-fledged oil-field riser. Atoll drilling might be more efficiently done using a cheap jack-up rig. Arctic drilling will almost certainly require a special platform.

We also note the obvious division of needs in the program between those requiring a small number of technically difficult, time-consuming deep holes and those requiring hundreds of technically straightforward shallow holes. The latter objectives include much of the hydraulic piston coring proposed by Workshops 1 and 5, the geochemical mapping program of Workshop 2 and the global stress program of Workshop 4. All these needs could be filled to a significant degree by a smaller and less expensive vessel than the *JOIDES Resolution* with capabilities of hydraulic piston coring followed by 50 meters of basement penetration. Such a vessel could also re-enter holes previously drilled by the *JOIDES Resolution* for logging, downhole experiments and deployment or recovery of downhole instruments. The specification of a ship to meet these needs is given in the chapter on alternate platforms. Running such a vessel for 200 days a year would cost about $ 4 M annually and would significantly increase the program's capability. The additional potential obtained by leasing temporarily this and other alternate platforms must be investigated carefully. *We recommend to consider the possibility of increasing the budget by as much as an additional 40% ($ 14 M) per year to obtain an improved, more efficient program using diversified drilling platforms within the framework of international technological cooperation.*

ADVISORY AND PLANNING STRUCTURE

Long-range thematic planning will need to be implemented in order to keep the necessary continuity required by the experimental approach of the programs proposed. Fundamental changes in the present planning and advisory structure will thus have to be made. One of the changes we recommend is the establishment of program management groups to oversee the long-term implementation of thematic programs. This is necessary for the continuity of drilling programs extending over long periods, involving a large interdisciplinary participation and requiring extensive long-range technological developments. Examples of such programs are the illustrative experiments described above. The lifetime of the program management groups should be from the inception of the program through the data gathering phase.

A second important recommendation we make is to ensure active and wide participation of the scientific community at large in the drilling program. The success of COSOD II was to a significant extent related to its ability to involve parts of the scientific community outside of the traditional ODP community. Thus access to the program should be made easier. We suggest that well publicized announcements of opportunity be made to solicit proposals for the long-range programs. All proposals, whether solicited or not, should be evaluated by the new thematic advisory structure, but only following independent external reviews.

BENEFITS

The drilling program that we propose here has important implications for society in three main fields, understanding the causes and consequences of climatic change, determining the response of biological systems to environmental change, and improving our methods for determining global resources.

Investigation of climatic change has clear social importance. Not only will the longer time span covered by ocean drilling give a clearer perspective on causes of climatic change, but the ancient record contains evidence of events as rapid in their action as those now affecting the environment because of man's activities. For example, computer models calibrated with data of the past can be used to predict the climatic response to an increase in atmospheric carbon dioxide. Studying the recovery of the environment from such past crises will clearly help us understand our own.

The biosphere has strong links with the physical and chemical environment, with a complex pattern of feedback, which is not easy to predict. We believe that our new biological program will have an important role in quantification both of the nature and rate of response of biological systems to environmental crises and of the active role of the biosphere itself in maintaining Earth as a life-supporting system.

Not only will the global fluid flux program give important constraints on the element cycling on which the biosphere and organic resources depend, but it will improve substantially our understanding of the genesis of many metal deposits, such as the poly-metallic sulfides now under survey in several parts of the mid-ocean ridge system. The study of the fluid flow in the subduction zones might also reveal a relationship with the earthquake cycle in these large earthquake-prone areas.

The importance of past drilling in resource evaluation has been demonstrated by the cooperation that ODP receives from major oil companies and the use they make of ODP drilling results. The new program will not only test profoundly some of the models used in oil exploration, such as the sealevel curve and models of fluid migration in the subsurface, but will investigate the distribution of oil source and reservoir rocks at particular times and will calibrate some of the least understood parts of the seismic stratigraphic record.

LINKS WITH OTHER GLOBAL PROGRAMS

Objectives shared with other global scientific research programs present important opportunities and challenges for the ODP. Many of these other global programs require new data and new ideas that can only be obtained by ocean drilling. Moreover, they provide a global framework of information and concepts that is important for the interpretation of data acquired by the ODP. *We recommend that the possibility of collaborating with other global scientific programs be carefully considered.*

Below, we briefly mention some of the more important existing programs.

The International Geosphere-Biosphere Program (IGBP) on Global Change, which is being established by the International Council of Scientific Unions (ICSU), depends on the record of past global change that is preserved in the ocean basins, and on an enhanced understanding of the chemical fluxes between the oceanic lithosphere and the oceans and atmosphere. It provides opportunities for linking studies of chemical, physical and biological processes on the ocean basins to those in the rest of the global system. The IGBP provides links with the World Climate Research Program (WCRP) and the World Ocean Circulation Experiment (WOCE), the Tropical Ocean and Global Atmosphere (TOGA) Program and the Global Ocean Flux Study (GOFS). The Inter-Union Commission on the Lithosphere (ICL), also established by ICSU, provides links to the Global Stress Mapping Program, the World Seismological Network, the Global Geoscience Transects Program, a Working Group on the Oceanic Lithosphere, and a Coordinating Committee on Continental Drilling, which provides links to a number of national continental scientific drilling programs with objectives that overlap some of those of the ODP. The Global Sedimentary Geology Program, recently established under the International Union of Geological Sciences (IUGS), provides links between the sedimentary record in the continents and in the oceans. The RIDGE (Ridge Interdisciplinary Global Experiment) Program has a unifying goal to understand the physical, chemical and geological causes and consequences of energy transfer within the global ridge system through space and time.

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WORKING GROUP POSITION PAPERS

Scientific Goals of an Ocean Drilling Program Designed to Investigate Changes in the Global Environment

Prepared by WORKING GROUP 1 (see p. 9)

ABSTRACT

Purpose. The purpose of this chapter is to identify first-order scientific questions about global environmental change that can be addressed by ocean drilling, and to recommend a strategy of drilling, logging and sampling that will contribute significantly to their resolution over the next ten years. Rather than a detailed program plan, we seek a conceptual framework within which proposals to advance our knowledge of global environmental change by ocean drilling can be evaluated.

Definition. Under the terms of reference for COSOD II, a "global environmental change" is defined as a change in the global climate system, *i.e.*, a change in the earth's outer fluid envelope or the surface of the land. Accordingly, our focus of attention is not on the physical, chemical, biological, acoustical or magnetic properties of the ocean sediment *per se*, but on information the sediment column contains about changes in the atmospheric composition and wind-field ; changes in the chemical composition, density structure, and circulation of the surface and deep ocean ; changes in the land surface ; changes in the distribution and volume of ice ; and changes in the sealevel. For operational reasons, we have found it convenient to discuss changes in sealevel separately from changes in other aspects of paleoclimate.

Paleoclimate. In the area of paleoclimate, two first-order goals of the scientific drilling program are to find out how global climate has changed over geologic time, and to understand the causes and mechanisms of these changes. Twenty years of exploratory drilling have made major progress towards the first goal. At the same time, the art of numerical modeling of the atmosphere, ocean, and ice sheets has advanced to the point where major advances towards the second goal come into reach. Our strategy is based on the idea that the changes we observe fall into two distinct categories and occur in two distinct frequency bands. On the one hand are the trends, oscillations, and steps which occur as a response to tectonic processes acting on timescales of a few million years and beyond. These features represent major changes in the climatic mode that are associated with major differences in thermal regimes, in the global pattern of winds, and in the chemical mass balances and three-dimensional patterns of ocean circulation. On the other hand are the orbitally driven oscillations which appear on timescales of 20-400 ka in our record wherever the sampling density is adequate.

The fact that the amplitude (and frequency) of the orbitally driven responses change from one climatic mode to another is a clear indication that the sensitivity of the system's response at these frequencies is modulated by its (modal) response to tectonic forcing at lower frequencies. Since fundamental radiation physics of the forcing in each orbital band is known quantitatively, and general circulation models of the atmosphere and ocean give us quantitative insights into the system's response to tectonic forcing, there is now an opportunity to formulate and test quantitative models of the mechanisms of climate change in both frequency bands. In short, we can now find out how the system works by conducting experiments in which observations (the geological record of climate) are compared with theory (quantitative predictions of models).

Sealevel. In the area of sealevel, a first-order goal of scientific drilling should be to improve our knowledge of the history of global sealevel changes. For pre-late-Pleistocene times, the problem of determining the amplitude and timing of major oscillations in global sealevel is unresolved. Our strategy for solving this problem in the Cenozoic is to compare the results of three independent approaches. The atoll approach, which is based on recent developments in stable-isotopic correlation of carbonate sequences, uses the stratigraphic record of atoll carbonates as dipsticks in regions having simple subsidence histories. The passive margin approach derives an estimate of global sealevel from stratigraphic information about relative sealevels on different continental margins. The isotopic approach infers changes in global ice volume from the isotopic composition of oceanic microfossils. Because each of these approaches has a different set of assumptions and limitations, it should in principle be possible to constrain knowledge of Cenozoic sealevel history by comparing the three sets of estimates.

Drilling Requirements. Drilling requirements of a program designed to investigate changes in the global environment are outlined and prioritized. Three experimental arrays are needed which, together with an interactive modeling effort, are designed to determine the history of global sealevel and the causes of important changes in climate during the Cenozoic. These include a paleoclimatic array capable of monitoring changes in the oceanic record of climate as a function of time, space, and paleodepth ; and two sets of transects designed to provide crucial information about the history of sealevel, three across selected atolls, and three across selected passive margins. In addition, we recommend three sets of exploratory drillsites designed primarily to discover new facts about the history of the Arctic Ocean, about continental margins and the adjacent lands, and about older parts of the marine sedimentary record.

INTRODUCTION

Purpose

The purpose of this chapter is to identify first-order scientific questions about global environmental change that can be answered by ocean drilling, and to recommend a strategy of drilling, logging, and sampling that will answer these questions over the next ten years, or contribute significantly to their resolution. Rather than a detailed program plan with specific drilling targets and a long list of disciplinary problems, we seek a conceptual framework within which proposals to advance our knowledge of global environmental change by ocean drilling can be evaluated.

Definition of Global Environmental Change

To achieve this purpose, we need first a clear definition of what "global environmental change" means in the present context. Under the terms of reference laid down by the COSOD II Steering Committee, global environmental change is a change in the global climate system, *i.e.*, a change in the earth's outer fluid envelope or the surface of the land. Accordingly, our focus of attention is not on the physical, chemical, biological, acoustical, or magnetic properties of the ocean sediment *per se*, but on information the sediment column contains about changes in the atmospheric composition and wind-field ; changes in the chemical composition, density structure, and circulation of the surface and deep ocean ; changes in the land surface ; changes in the distribution and volume of ice ; and changes in sealevel.

Climate and Sealevel : an Operational Distinction

The processes which change sealevel and those which change climate are so intimately related that there is little scientific basis for drawing a sharp line between research efforts designed to elucidate them. Yet the requirements of a drilling program designed primarily to improve our knowledge of eustatic sealevel, and a program designed primarily to investigate climatic change, are sufficiently distinct operationally that we have found it convenient to discuss them separately.

Submarine Geology in COSOD I and COSOD II

In the Report of the first Conference on Scientific Ocean Drilling (COSOD I), three working groups deal with the origin, evolution, and magnetic properties of marine sedimentary sequences. Separate discussions are devoted to opportunities for understanding local sedimentary processes, basin-wide sedimentary sequences, post-depositional alteration of sediments, and the past behavior of the earth's magnetic field. The situation is very different in COSOD II, where only Working Group 1 (which prepared this paper) was charged with analyzing the sedimentary record in detail. Furthermore, as discussed below, the focus of attention in this paper is on the environmental information that the sediment column contains, rather than on its chemical, physical, and geophysical properties. As a result, many significant problems in the broad field of submarine geology - problems whose resolution would significantly improve our ability to read the record of environmental change from the sediment column - are not addressed in the document. However, as our estimates of drilling time include provision for attaining sedimentological objectives, we see no fundamental difficulty in accomplishing both environmental and sedimentologic goals in a drilling program where, traditionally, each cruise has multiple objectives.

Acknowledgements

This chapter grew out of a white paper prepared for the COSOD II Conference by the members of Working Group 1. In its present form, it includes significant contributions made both orally and in writing by most of the 70 scientists who attended Workshop 1 on July 6-8, 1987. We also gratefully acknowledge drafts of portions of this paper that were contributed by: M.A. Arthur, W.A. Berggren, J. Farrell, L. Gahagan, R. Halley, W.W. Hay, R. Keir, J. Kennett, D.V. Kent, R.L. Larson, K. Ludwig, R.K. Matthews, K.G. Miller, T.C. Moore, Z. Peterman, M. Rankin, W. Ruddiman, J. Sclater, C. Scotese, N.J. Shackleton, C. Shaw, K. Simmons, C.P. Summerhayes, P. Westbroek, and F. Woodruff.

We wish to acknowledge our debt to the authors of several official reports that were prepared with the objectives of COSOD II in mind and that we found useful as resource documents : Report of the Canadian Ocean Drilling Workshop, Montreal, September 25-27, 1986 ; Report of the UK Workshop on the Ocean Drilling Program (Sediments and Ocean History Panel), London, May 1987 ; and "The Future of Ocean Drilling", a report of a workshop organized by the ESF Consortium for Ocean Drilling (ECOD), Gwatt, March 18-20, 1987.

Finally, we acknowledge with special thanks our debt to the authors of the COSOD I Report whose insights and analysis provided an essential background for our efforts. Our report, in fact, should be thought of as an addition to the structure they created, which remains a valuable guide to many aspects of deep sea drilling, including several that are not treated in detail in this report.

SUMMARY OF MAJOR FINDINGS AND RECOMMENDATIONS

Progress since COSOD I

Paleoclimate

The years since COSOD I have witnessed major advances in our knowledge of climate change on geological timescales. These advances include improvements in our ability to date and correlate climatic changes ; and to measure them by logging, by laboratory analysis of samples, by estimating sediment fluxes and by the use of new chemical and isotopic indicators. In turn, these primary developments have led to the discovery and better definition of physical and chemical changes in the atmosphere and ocean. Research over the past seven years has also led to better knowledge of changes in ocean basin geometry, which act as a major forcing function of climate ; and a far more precise evaluation of the influence that changes in orbital geometry have had on Cretaceous and Cenozoic climates. At the same time, improvements in general circulation and chemical models of the atmosphere and ocean, in models of ice sheets, and in models that calculate continental elevations from information on marine sediment, have opened new opportunities for conducting numerical experiments with the geological record of climate.

Sealevel

Substantial progress has also been made on the problem of determining the history of eustatic sealevel. These advances include widespread application and analysis of coastal onlap curves derived from seismic stratigraphy ; substantial improvements in the $\delta^{18}O$ database from which ice-volume estimates can be made ; the development of models of the Antarctic ice sheet, and of the isotopic composition of glacial ice ; the advent of an important new Sr isotope method for dating marine carbonates ; the application of that method to atoll limestones containing sealevel information ; and improvements in geophysical models of crustal subsidence.

Experimental Opportunities

Like any science, historical geology has two basic goals : to find out what happens and to explain how the system works. As summarized above, the years since COSOD I have made major contributions to our knowledge of what happened in earth history. We know, for example, that at certain times in the past the climate system operated in very different modes than it does today - as evidenced by the amount and distribution of ice on land, the level of the sea, the chemistry of the ocean, the position of the oceanic fronts, and the structure and vigor of the planetary wind-field. And we know, with some precision, two of the *fundamental causes* which drive changes in climate. One of these is the change in the geometry of land and sea. This drives changes in climate on timescales of several millions of years and beyond. The other is the change in geometry of the earth's orbit, which causes changes in climate on timescales between 20 000 and 400 000 years. In addition to these tectonic and orbital influences, other forcings external to the climate system may well be important : hydrothermal fluxes, for example, or biologic evolution, or the fluxes of energy and material from outer space. But as these forcings are not as yet so clearly defined, our strategy is focused on unravelling the environmental responses to tectonic and orbital causes.

A Global System View

In designing such a strategy, it is useful to consider the entire hydrosphere, atmosphere, cryosphere, biosphere, and land surface as the climate system (Fig. 1). Given our knowledge of the *input* to the climate system (the tectonic and orbital forcing functions that are external to the system), and the *output* of the system (the climatic record), we now have a once-in-a-century opportunity to identify and understand the coupled physical, chemical and biological *mechanisms* that are the immediate causes of each observed change in climate (Imbrie, 1985). This opportunity, in essence, is to conduct *experiments* in which observations (the geological record of climate) are compared with theory (quantitative predictions of models). But so far, efforts to explain how the system works have largely taken the form of qualitative, *conceptual models.* Although such models are always the starting point for developing quantitative explanations of natural phenomena, they have severe limitations as applied to the climate system in which the responses of atmosphere, ocean, ice sheets, and biota are strongly coupled, often non-linearly. These models are essentially verbal narratives, difficult to pin down and test because they fail to make quantitative predictions of the fraction of the total variation observed that is caused by a particular mechanism. The time has come, we believe, for historical geology to begin to move out of the *exploratory phase* - as essential and exciting as this has been - and into an *experimental* phase in which quantitative predictions grounded in fundamental physics, chemistry, and biology, are compared with geological observations (Rea, 1987). In short, the time has come to disentangle the web of external influences and internal responses, and get down to the fundamental problem of cause.

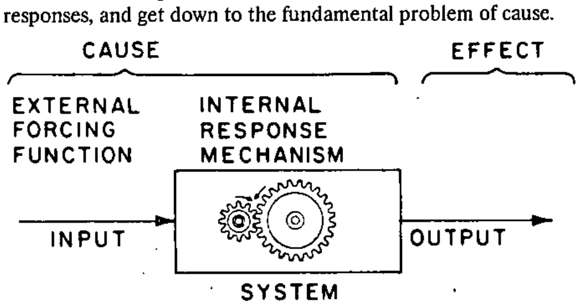

Figure 1. The system concept. As applied to the problem of environmental change, the input to the climate system is defined as a time series of tectonic and orbital variations. The output is a time series of climatic and sealevel observations. The fundamental or remote cause of an observed variation in the environment is the associated change in the external forcing ; the immediate or proximal cause is the system's response.

The Climate Problem

How do these principles apply to the investigation of paleoclimates, where we know that the present climatic state is not in any sense normal and that many past climates have been very different from those of today ? Our strategy is based on the idea that the climatic changes we observe fall into two distinct categories and occur in two distinct frequency bands. On the one hand are the trends, oscillations, and steps which occur in response to tectonic processes operating on timescales of a few million years and beyond. These features represent major changes in the climatic mode that are associated with major differences in thermal regimes, in the global pattern of winds, and in the chemical mass balances and three-dimensional patterns of ocean circulation. On the other hand are the orbitally driven oscillations which appear on timescales of 20-400 ka in our record wherever the sampling density is adequate.

The fact that the amplitude (and frequency) of the orbitally driven responses change from one climatic mode to another is a clear indication that the sensitivity of the system's response at these frequencies is modulated by its (modal) response to tectonic forcing at lower frequencies. *Since the fundamental radiation-physics of the forcing in each Milankovitch band is known quantitatively, and general circulation models of the atmosphere and ocean give us quantitative insights into the system's response to tectonic forcing, there is now an opportunity to formulate and test quantitative models of the mechanisms of climate change in both frequency bands.* This is the theme of the next section.

The Sealevel Problem

We know that global sealevels have varied markedly, on the order of 200 m during the Cenozoic alone, in response to global tectonic forces which alter the volume of the ocean basin, and to climatic forces which change the volume of water stored on land as ice. For the late Quaternary, we know that glacioeustatic fluctuations occur on the order of 100 m at (orbital) frequencies. For earlier times, the problem of determining the amplitudes and frequencies of eustatic fluctuations is unresolved, with different data sets yielding conflicting estimates. We argue below that these conflicts can be resolved by an appropriately organized experimental program which combines drilling and modeling. Given the importance of global sealevel for a wide range of geological disciplines, it is clear that a first-order goal of scientific drilling should be to improve our knowledge of the history of global sealevel.

Exploration Opportunities

The fact that two decades of deep sea drilling have led to the discovery of many striking changes in global climate, and that these changes cry out for better definition by targeted drilling programs and fuller explanation tied to quantitative modeling, should not blind us to the need of a continuing effort in exploration. In a later section, we argue that this need is clearest in areas such as the Arctic Ocean, where there has been essentially no scientific drilling ; and along continental margins, where there are opportunities to extend our knowledge of the regions of high productivity associated with boundary currents, and to read the record of changing climate on the adjacent lands. We also argue for the need to penetrate older portions of the sediment column, where the existing coverage is sparse and there are unfulfilled opportunities for investigating how the ocean behaved during the early Cretaceous and even older phases of the breakup of Pangea.

Drilling Requirements

The drilling requirements of a program designed to investigate changes in the global environment are outlined and prioritized in Table 1. Three experimental arrays are indicated

Table 1. Drilling requirements of a program designed to investigate changes in the global environment.

Requirement	Definition	Purpose	Priority in terms of this program
1. Paleoclimate array	Transects of double-cored, HPC and XCB sites to define changes in each ocean basin as a function of time, paleodepth, and space ; and on the adjacent lands	*Understand causes and mechanisms of climate change *Monitor oceanic circulation and transport of heat and nutrients *Document ice volume history and associated sealevel changes *Improve biomagnetostratigraphy and chronology *Document organic evolution *Determine rates and processes of sediment accumulation	1
2. Atoll transect	Three transects across living and drowned atolls with simple subsidence history	*Constrain models of eustatic sealevel history	1
3. Passive margin transects	Three shelf-to-basin transects away from the North Atlantic, coordinated with seismic profiling and land drilling	*Compare relative sealevel history of margins with different tectonic evolution	1
4. Arctic Ocean Drilling	Drill sites in the Arctic Ocean basin	*Obtain knowledge of Arctic Ocean history	1
5. Continental margin drilling	Transects perpendicular and parallel to North Atlantic and other margins	*Document oceanic and continental history in high-deposition-rate areas with strong environmental gradients	2
6. Deep stratigraphic tests	Drilling into oldest sediments	*Extend our knowledge of early evolution of the oceans and processes of sediment accumulation	2
		*Improve biostratigraphy and chronology	2

which, together with an interactive modeling effort, are designed to determine the history of global sealevel and the causes of important changes in climate during the Cenozoic. These include a paleoclimatic array capable of monitoring changes in the oceanic record of climate as a function of time, space, and paleodepth ; and two sets of transects designed to provide crucial information about the history of sealevel, three across selected atolls, and three across selected passive margins. In addition, we recommend three sets of exploratory drillsites designed primarily to discover new facts about the history of the Arctic Ocean, about continental margins and the adjacent lands, and about older parts of the marine sedimentary record.

Benefits

That the program of drilling recommended in this paper will move the earth sciences forward in their quest to document and understand the past is self-evident. Beyond this, we see substantial benefits to society as a whole - to a society that is now coming to grips with major environmental issues associated with human contributions to climate change, and with the need to determine for this and future generations the distribution and extent of our offshore resources of petroleum.

Understanding Global Change

Our concepts of earth history and how the earth functions are undergoing a revolution, a revolution to which deep sea drilling has made a major contribution. Not only have we come to accept the fact that oceans spread and continents drift, but we now know that the present climate is but one state of a dynamic, constantly changing system. Ice sheets have come and gone, monsoon rains intensified and diminished, atmospheric temperatures and the associated levels of oceanic and atmospheric CO_2 changed markedly, and the ocean changed from its present stirred and oxygenated state to conditions marked by widespread deficiency and a radically different thermal structure.

Although the climatic records derived from ODP cores are capable of documenting such changes on timescales of decades and centuries in a few nearshore sites, in general our data describe changes on timescales of several millenia to many millions of years. *The value of these records is therefore not that they will permit us to forecast the future in a time-dependent sense, but that as a part of an experimental, data-modeling effort, they will teach us how the system operates - and in particular how sensitive the life-supporting system is to perturbations in its boundary conditions, whether those perturbations are natural or man-made.*

We are living at a time of rapid climatic change, and man is contributing to these changes by his own activities. By entering strongly into the carbon cycle, we have our thumb on one of the pressure points of the system - the insulating trace gases of carbon dioxide and methane which largely control the retention of heat received from the sun. As we engage unwittingly in this global experiment, it seems mandatory to learn as much as we can about the experiments that Nature herself has undertaken, which are recorded in sedimentary sequences, and which offer important insights into the workings of the global system.

Determining Offshore Resources

Industry has considerable interest in the results of deep ocean drilling, which is a beneficial source of useful information for global petroleum exploration offshore. DSDP and ODP made major contributions to petroleum geology by (1) providing major revisions in biostratigraphy ; (2) documenting the existence, nature, and extent of potential petroleum source rocks (black shales) in deep water ; (3) evaluating the hydrocarbon potential of parts of the continental margin unsampled by industry ; (4) providing hard geological data for the calibration of industry's long seismic lines ; and (5) improving industry's understanding of the evolution of petroliferous continental margin basins. In effect, DSDP and ODP holes are like free COST wells for industrial use.

Industry has shown its interest by (1) sending its paleontologists, sedimentologists, and geochemists on DSDP/ODP cruises ; (2) doing shore-based work on DSDP/ODP samples for publication in DSDP/ODP reports ; and (3) serving on DSDP/ODP advisory panels. This is the thin end of the wedge ; most of industry's use of DSDP/ODP data is proprietary. For the future, it is fair to assume that industry (especially multinational oil companies) will continue to be interested in deep ocean drilling as ODP opens new frontiers.

Exploration drilling is moving into ever deeper water, making more detailed knowledge of ocean history progressively more necessary for accurate pre-drill technical appraisals of hydrocarbon prospects offshore. *Industry will therefore benefit directly from enhanced understanding of how the oceans work, and particularly from improvements in our ability to model the possible occurrence, character, and potential of petroleum source rocks deep beneath the world's continental margins.*

PALEOCLIMATIC CHANGE

Scientific Goals

Two first-order goals of the scientific drilling program are to find out how global climate has changed over geologic time, and to understand the causes and mechanisms of these changes. In the earlier stages of deep sea drilling, the descriptive aspects predominated. But as a database of increasingly higher quality and quantity has grown, and as the art of numerical modeling of atmosphere and ocean has developed, we are fast approaching a stage at which the identification of causes and of mechanisms comes into reach. We here attempt to identify those areas of research which are likely to contribute most to this goal, beginning with a summary of progress since COSOD I, proceeding to an evaluation of present opportunities, and concluding with a set of general drilling recommendations.

Progress since COSOD I

The six years since COSOD I have witnessed major additions to our knowledge of paleoclimate, and to our store of techniques for reading and interpreting the paleoclimatic record. As indicated below, these developments have occurred across a broad range of disciplines, including geology, geophysics, geochemistry, climatology, and oceanography. They include improvements in our knowledge of the tectonic and orbital forcing functions ; in our understanding of the response mechanisms ; in stratigraphy and geochronology ; in our ability to decipher terrestrial changes from ocean records ; in our knowledge of climate history ; and our ability to model the atmosphere, the ocean, the ice sheets, and land elevations. Clearly, it is impossible to provide comprehensive references to this body of work. But the reader will find excellent summaries of recent advances in eight volumes which have appeared since 1984. Two stress responses in the Milankovitch band : Arthur and Garrison (1986), and Berger *et al.* (1984). The rest cover a wide range of frequencies and times, with considerable emphasis on geochemical modeling : Hansen and Takahashi (1984), Hsü (1986), Hsü and Weissert (1984), Kennett (1985), Summerhayes and Shackleton (1986), and Sundquist and Broecker (1985).

Understanding the Forcing Functions

The circulation of oceans and atmosphere responds to various factors but is constrained by two forcing functions : the pattern of energy input, and the control exercised over circulation patterns by topography - oceanic and continental.

Energy Input : Milankovitch Forcing. The earth's orbital variations (precession, obliquity, and eccentricity cycles) change the distribution of insolation, by latitude and by season. By the time of COSOD I it had become clear that Pleistocene glacial cycles had been driven by these variations, but there was widespread feeling that such climate cyclicity depended primarily on feedback effects from glacial albedo, and were therefore restricted to glacial times. Since then, we have learned that cycles at orbital frequencies pervade the entire stratigraphic record in climate-sensitive facies (Fig. 2, 3), and have throughout played an important role in changing the distribution and intensity of monsoon-related rainfall, the distribution of land vegetation, and the temperature, productivity and geochemistry of the ocean. It is now clear that the 100 000-year eccentricity-driven ice-volume cycle that dominates the high-latitude record on land and in the ocean over the past 900 ka was <u>not</u> a feature of the climatic response during the late Pliocene and early Pleistocene (Fig. 2). But the amplitude of the 41 000-year obliquity-driven ice-volume cycle, and associated features of the deep-water circulation, remained relatively constant during the entire interval just discussed. We therefore assume that long-term changes in climate during this interval must have modulated the system's sensivity in the 100 000-year band. Although the mechanism of this modulation remains obscure, suspicion rests on the CO_2-ocean-feedback loop.

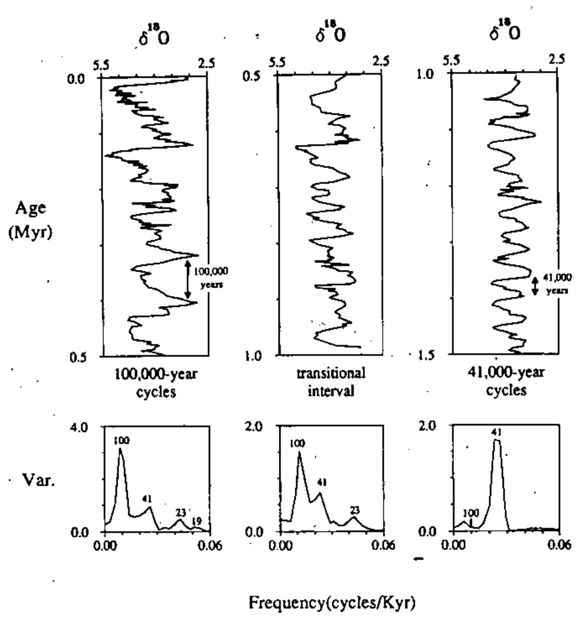

Figure 2. Stable-isotopic ($\delta^{18}O$) record from benthic foraminifera at North Atlantic DSDP Site 607 (41°N, 33°W). The downcore trends (top) and spectral analyses (bottom) indicate a transition from 41 000-year cycles during the Matuyama Chron (right) to 100 000-year cycles during the Brunhes (left). The transition occurred during the middle Pleistocene (center). From Ruddiman *et al.* (in prep).

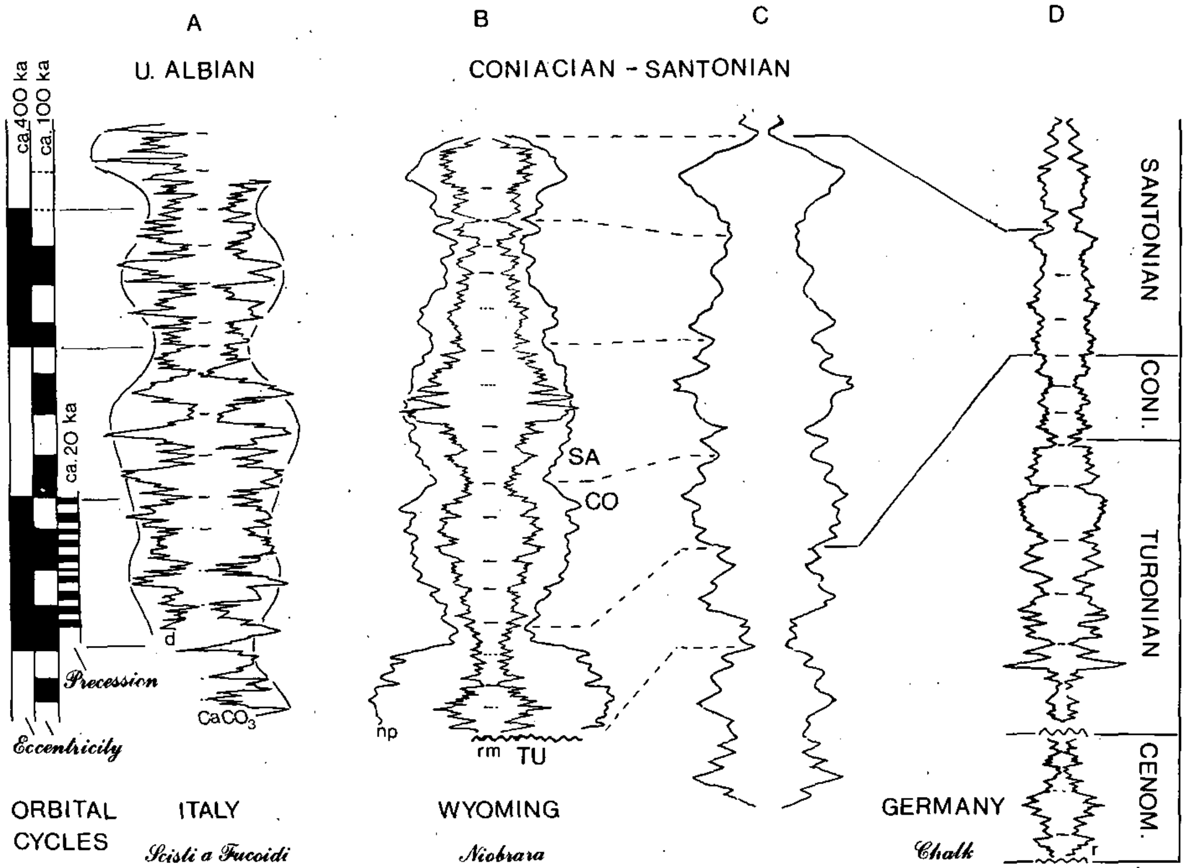

Figure 3. Signatures of "precession-eccentricity syndrome". The high-frequency signal is the precession-related (c. 21 ka) alternation of low-carbonate/high-carbonate bedding couplets; these are grouped into bundles corresponding to the 100 ka short-eccentricity cycle; envelope curve delineates the 400 ka long-eccentricity cycle. A: Albian, Italy: core segment inferred to represent 1600 ka. Orbital signals occur in both scan of darkness (left) and scan of calcium carbonate (right). From Herbert and Fischer, 1986; timing based on mean sediment accumulation rates. B: Late Cretaceous (Coniacian-Santonian) Niobrara Formation, Wyoming: resistivity microlog and neutron porosity log, Golden Buckeye core, Laramie County; from Fischer, in prep.; timing based on length of Coniacian stage (approximately 1 Ma) here incomplete and represented by two long-eccentricity cycles (800 ka). C: enlarged segment of D, for comparison with B. D: Late Cretaceous (Turonian-Santonian) chalk of northern Germany: normal resistivity log, precession not resolved. Preussag-Texaco N° 1 Offenseth. Timing based on number of long-eccentricity cycles (6) in Turonian (ostensibly 2.5 Ma). Coniacian represented by three such cycles (A. Fischer, in prep.).

It has also become clear that away from the ice sheets during Quaternary, Pliocene, and perhaps earlier times, 23 000-year, precession-driven changes in the intensity of the Asian monsoon are locally the most significant climatic response. Here the basic physics of the response is simple enough (high summer radiation = strong monsoon) that atmospheric general circulation models have been able to simulate the observed responses with reasonable fidelity (Prell and Kutzbach, 1987).

Ocean Basin Geometry. Our ability to reconstruct the geographic positions of the continents, their elevations and the geometry of the sea floor at various points in geologic time is a function of our knowledge of ocean floor basement ages and the history of plate motion for the geologic time under consideration. Substantial advances since the COSOD I meeting of 1981 were summarized on the map by Larson *et al.* (1985), "The Bedrock Geology of the World". This map in turn has been utilized by Scotese *et al.* (in press) to produce a series of nine plate tectonic reconstructions by an interactive graphics technique.

Figures 4 and 5 show sample reconstructions for the Oligocene-Miocene boundary (magnetochron 6B, 23.0 Ma) and the Cretaceous-Tertiary boundary (magnetochron 29, 66.2 Ma). The relatively small gaps (white areas) and overlaps (black areas) at paleoridge crests are indications of the consistency (and probable accuracy) of the Larson *et al.* (1985) map and of the precision of the computer graphics reconstruction technique. Not suprisingly, the reconstructions, and by implication the Larson *et al.* (1985) map, contain larger errors in the Cretaceous and Jurassic. This indicates a continuing need for mapping and reconstruction work on late Mesozoic portions of the Indian Ocean and western Pacific sea floor.

Such reconstructions, at least for the Cenozoic, are accurate starting points for ocean basin geometry that can be used to frame paleocirculation and other paleoclimate modeling studies. Yet to be accomplished are similarly accurate, worldwide paleodepth maps based on our knowledge of basement ages, oceanic lithosphere cooling curves and hot spot morphologies. The two-dimensional reconstructions of Scotese *et al.* (in press) can be expanded into three-dimensional representations of the world's oceans at various points in time since the Middle Jurassic. These reconstructions will yield accurate histories of the opening of divergent "gateways", such as the opening of the Gulf of Aden or the Norwegian-Greenland Sea. They must be integrated with land geology and paleocurrent studies recorded by deep sea sediments to obtain accurate pictures of predominantly strike slip or closing gateways.

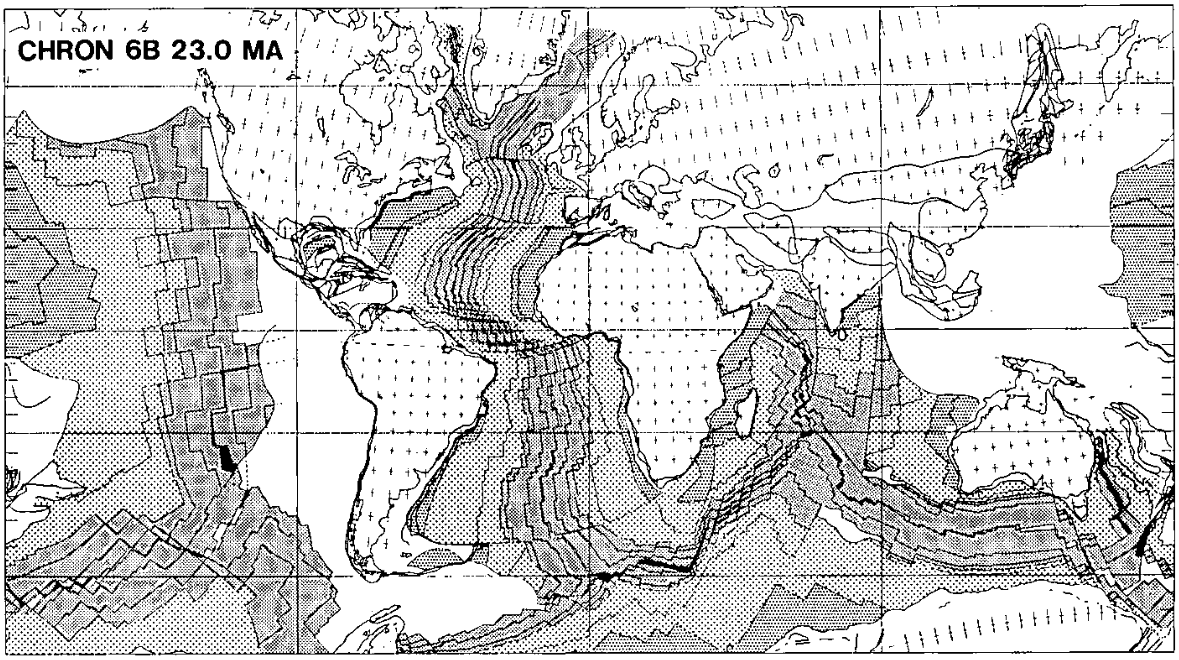

Figure 4. Worldwide tectonic reconstruction at the Oligocene-Miocene boundary (magnetochron 6B, 23.0 Ma) accomplished by rotating the 23.0 Ma ocean basin isochrons from "The Bedrock Geology of the World" map (Larson *et al.*, 1985) into coincidence at paleoridge crests. The small gaps (white areas) and overlaps (black areas) at paleoridge crests indicate the consistency (and probable accuracy) of the base map. The large white areas in the eastern and western paleo-Pacific are areas of oceanic lithosphere subducted since 23.0 Ma (Scotese *et al.*, 1987).

Figures 4 and 5 also show the inherent limitations of this technique. The increasingly large white areas in the older reconstructions indicate ocean floor that has been subsequently subducted, and thus cannot be used directly to constrain the reconstructions. Certain assumptions can be and have been made about plate boundary configurations and the symmetry of the spreading process to model entire ocean basins for the past 160 Ma (see, for instance, Engebretson *et al.*, 1985 for a model reconstruction of the Pacific basin). These integrated studies are only beginning as the ocean floor geophysicists and structural geologists from the surrounding continents meet (sometimes quite literally) at the shoreline to build an integrated model of the tectonic history of the evolution of coupled structural systems. One spinoff of such studies will be

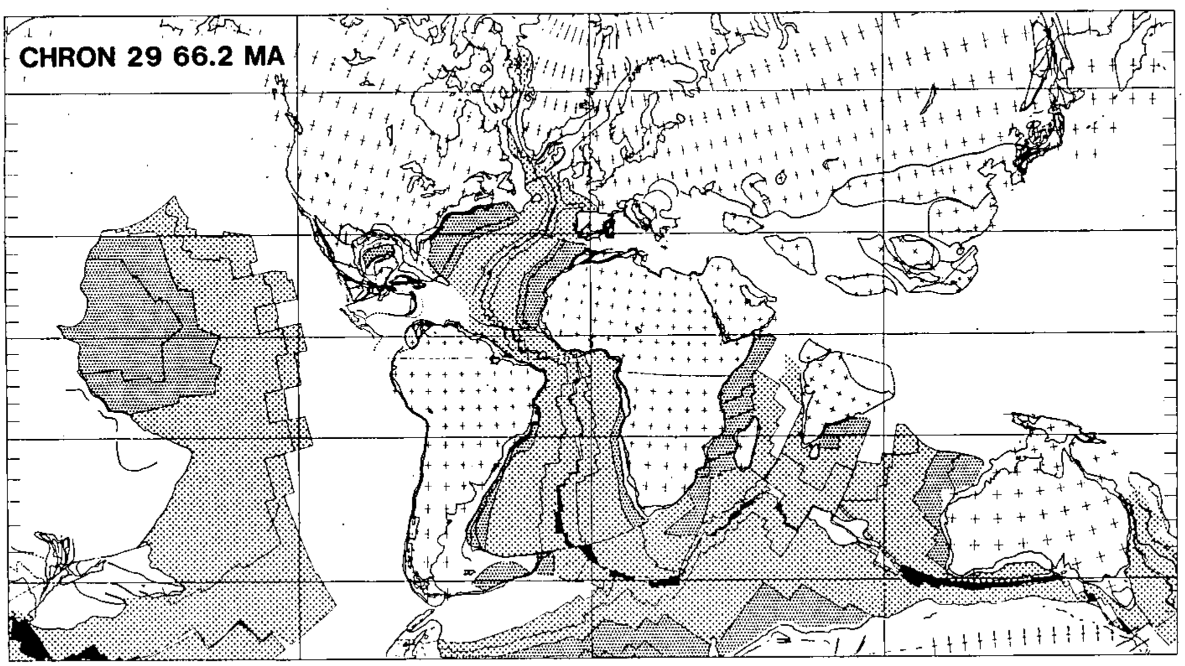

Figure 5. Worldwide tectonic reconstruction at the Cretaceous-Tertiary boundary (magnetochron 29, 66.2 Ma). The reconstruction technique and illustration format are the same as Figure 3.3 *in* Scotese *et al.*, 1987.

an enhanced knowledge of total ocean basin morphology as the most complete and consistent way to fill in the white spaces in the Scotese *et al.* paleo-ocean basins.

The ultimate limitation is reached at the maximun age of the present-day ocean basins, about 180 Ma, or Early Jurassic. At that point the continents quite comfortably fit into a conventional "Pangea" supercontinent. However, that was a relatively recent result in the Jurassic following the chaos of the Appalachian-Hercynian orogeny that was, in turn, the finale in a series of Paleozoic suturing events. Our knowledge of these events and the associated plate tectonic histories comes from the murky and usually disturbed records of the continents, predominantly those of structural geology and paleomagnetism. The early Mesozoic and Paleozoic deep ocean areas will forever be blank areas on the maps.

Understanding Response Mechanisms

The tools and data for a concerted attack on problems of global change are coming to hand. Sediment traps have brought new light to sedimentary processes at sea. The ice-core work shows unexpected fluctuations of the atmospheric carbon dioxide content, thus opening new vistas of paleoclimatology. Carbon isotope ratios promise to provide ways of mapping changes in ocean circulation. The emergence of Milankovitch cyclicity opens new insights into the earth's response to climatic forcing and promises great refinements in geochronology.

Sediment Flux. The rates of accumulation of the various kinds of sediments in the deep sea - carbonate, silica, organic matter, phosphate, terrigenous and volcanogenic materials, hydrogenic deposits - are fundamental to the quantitative representation of global geochemical balances, internal cycling in the ocean, chemical state of the ocean and atmosphere, and climate evolution. New fields have opened up as the result of sediment trap data and the capability to recover instantaneous sedimentation rates, and therefore to identify and quantify the various processes governing sediment flux and its components.

In principle, the results from sediment trap experiments, first summarized by Suess in 1980, make it possible to reconstruct the productivity of the ocean from sedimentation rate data on organic carbon (Sarnthein *et al.*, in press), as well as micropaleontological indices calibrated against the supply of organic carbon (Zahn *et al.*, 1986). Similarly, geographic coverage of the carbonate and silica flux from trapping provides a tie-in between rate of supply of biogenous matter with the productivity, a central linkage in the carbon cycle (Bruland *et al.*, 1984).

The demonstration that Pleistocene fluctuations in pelagic sedimentation, biogenous and abiogenic alike, are controlled by Milankovitch forcing (Fig. 2 ; Hays *et al.*, 1976) opened the possibility of deriving instantaneous sedimentation rates from the tuning of stable isotope (and other) records to the astronomically fixed driving function (Imbrie *et al.* 1984 ; Herterich and Sarnthein, 1985 ; Prell *et al.*, 1986). This tool, the "stratigraphic tuning fork", is applicable throughout the record, at least back to the Cretaceous (Fig. 3 ; Arthur *et al.*, 1984 ; Fischer, 1986 ; Herbert and Fischer, 1986). To use this tool we require excellent stratigraphy in continuous sections.

Atmospheric CO_2 Variations. One of the most significant scientific discoveries of the decade is the fluctuation of the atmospheric CO_2 over the last 160 000 years, obtained from the Vostok Antarctic ice core (Fig. 6 ; Barnola *et al.*, 1987). The Vostok record shows that atmospheric CO_2 levels rose dramatically by 80-90 ppm during the last two ice age terminations. The "sawtooth" shape of the Vostok record is particularly suggestive that atmospheric CO_2 changes dominate the important low frequency (100 ka^{-1}) components of Pleistocene climatic variations. This possibility is particularly important because of the struggle over the last decade to explain the 100 000-year power in many of the important time series records (*e.g.* ice volume, SST). The fact that the spectrum of variability in insolation has virtually no power in this band suggests the existence of some internal system-instability that is paced in some way by orbital forcing. The Vostok record may well point to the part of the climate system which transforms the insolation pattern to produce strong low frequency variations in climate. These same low frequency variations (100 and 400 ka^{-1}) dominate climatic variability during large segments of the past 100 Ma.

Large variations in the atmospheric CO_2 on timescales of millions of years have been proposed based on geochemical models (Berner *et al.*, 1983), climate models (Barron and Washington, 1985) and elements of the isotopic record (Arthur *et al.*, 1985) to explain the apparent warmth of the early Tertiary and Cretaceous. This research yields a whole new perspective on the importance of the coupled climate and chemical cycle system. In particular, the role of atmospheric CO_2 and the response of the earth system has become an integral part of understanding response mechanisms on a variety of timescales.

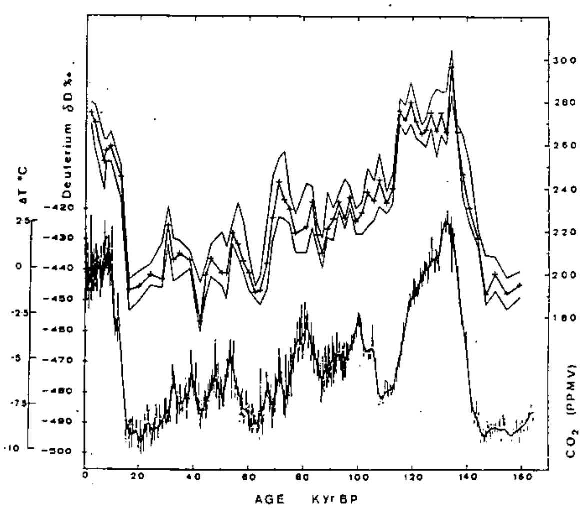

Figure 6. Parallel records of atmospheric CO_2 (upper with uncertainty envelope) and temperature change (lower, inferred from deuterium δD/H) over the last 160 000 years from the Vostok Antarctic ice core. Heavy line in lower curve is smoothed record (Barnola *et al.*, 1987).

The $CaCO_3$ System. On the timescales of orbital variability, the concentration of CO_2 in the atmosphere is mainly an expression of the chemical properties which are internal to the ocean and the upper 10-20 cm of ocean sediment (Broecker and Peng, 1982). Thus, the accumulation of $CaCO_3$ in ocean sediments is a powerful diagnostic of the chemical state of this system. Thermodynamic properties of $CaCO_3$ dictate that its solubility increases with increasing pressure (depth). One typically observes in the ocean a transition zone a few hundred meters thick in which sediments change from a high to a low $CaCO_3$ content. The depth of this transition zone is not constant within the ocean but varies as a property of global circulation patterns and both global and local differences in $CaCO_3$ production at the surface.

Farrell and Prell (1987) have produced a detailed record of $CaCO_3$ accumulation in the equatorial Pacific over the last four million years (Fig. 7). The record shows cyclic deepening and shallowing of this transition zone over a depth range from 4300-4800 m. During the last 1 Ma the main cycles are clearly 100 000 years in duration, and show evidence of an even lower frequency envelope of cycle amplitudes. The 100 000-year cycles give way to lower frequency oscillations between 1-3 Ma,

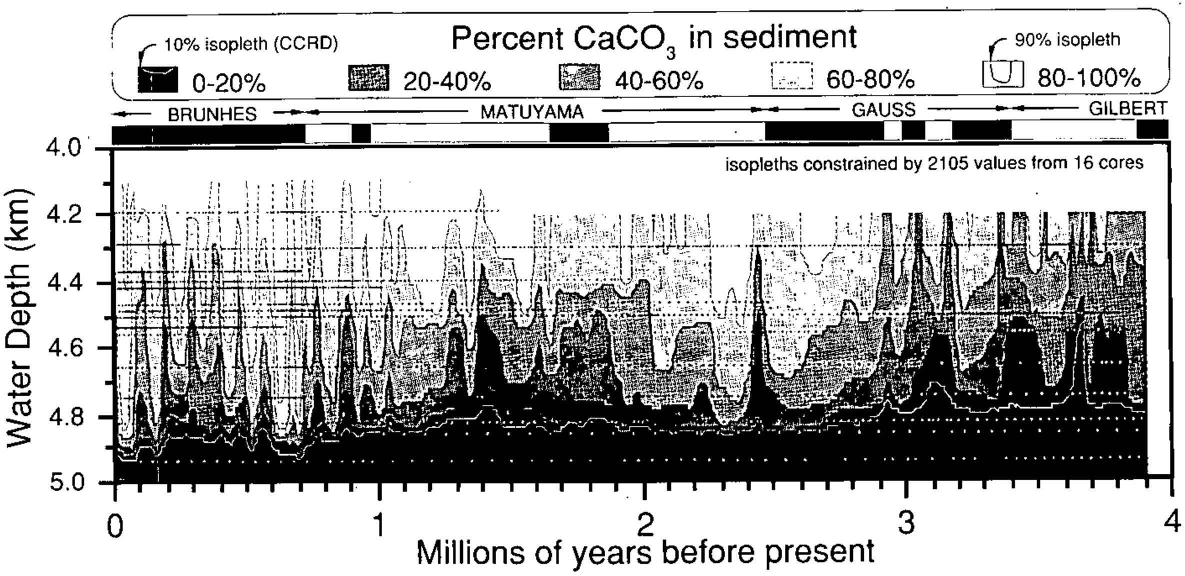

Figure 7. Bathymetric variations in central equatorial Pacific $CaCO_3$ preservation through time, as expressed by the sedimentary $CaCO_3$ content. 2105 values of weight percent $CaCO_3$ from 16 cores including DSDP Holes 573A and 574 were plotted against estimated age and core-site water depth (dots). The values were contoured with 6 isopleths at the 90, 80, 60, 40, 20, and 10 percent $CaCO_3$ levels. Since $CaCO_3$ contents can be used to estimate the apparent loss of $CaCO_3$ to dissolution, these levels represent losses of approximately 0, 56, 83, 93, 97, and 99 percent respectively, assuming that the flux ratio of $CaCO_3$ to non-$CaCO_3$ from the surface waters was temporally constant at 9 : 1 (Farrell and Prell, 1987).

with higher frequency cycles returning in the last million years of the record. This record provides an example of the mode-change concept discussed earlier, one which has some as-yet-unexplored relevance to the atmospheric CO_2 problem.

Peterson and Prell (1985) have produced a $CaCO_3$ record for the last million years in the Indian Ocean (Fig. 8). The data have been reported in units of a calcite dissolution index which records the relative degree to which $CaCO_3$ has been lost to solution. One can detect 100 000- and 400 000-year cycles and some barely resolvable higher frequency events. The two glacial terminations recorded as rapid CO_2 rises in the Vostok core show up as the downward plunges in the contours at 10 000 and 120 000 years. These plunges (toward low dissolution) are entirely consistent with an exhalation of CO_2 from the ocean which leads to enhanced preservation of $CaCO_3$ in the deep sea.

Chemical Tracers of Ocean Circulation. Chemical tracers, such as bomb Tritium, have played a pivotal role in understanding the modern ocean circulation. A growing number of chemical tools have been developed or proposed which can yield similar insights into past ocean circulation. One of the most useful of these tools is $\delta^{13}C$. The selective extraction of ^{12}C in photosynthesis depletes surface waters in that isotope, but as surface waters sink and age, ^{12}C is returned to them by respiration. Some benthic foraminifera record the $\delta^{13}C$ of bottom waters, and may thus be used to map the distribution of water masses. For example, Curry and Lohmann (1983) and Shackleton *et al.* (1983) have used vertical and horizontal gradients to evaluate past changes in deep water circulation. An important new tool to better constrain the interpretation of carbon isotopic studies has come from the use of Cd/Ca ratios (Boyle and Keigwin, 1982). The carbon

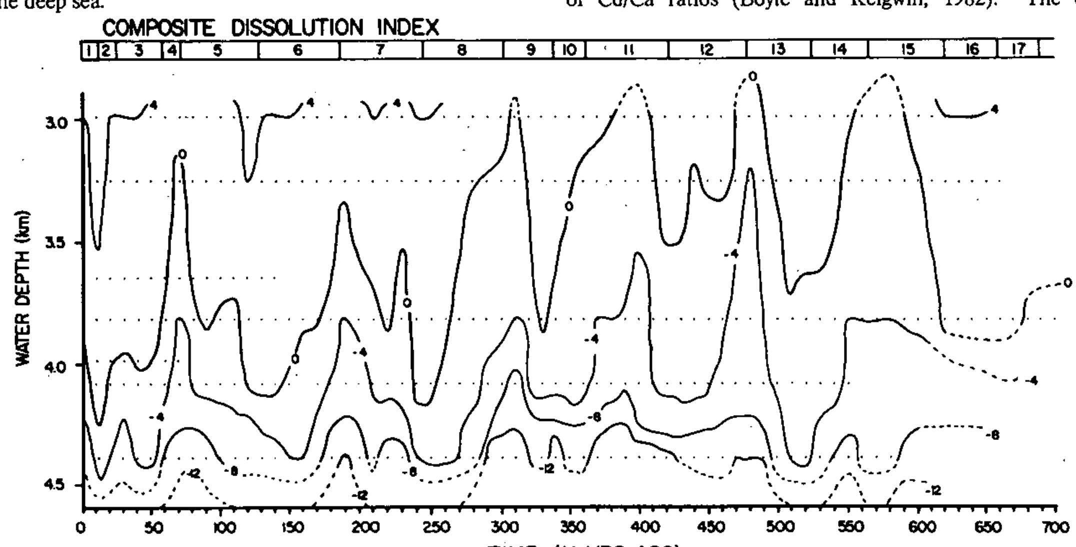

Figure 8. Bathymetric variations in relative preservation through time, as expressed by the Composite Dissolution Index. These values were plotted according to core depth and estimated age and then contoured. The numbered legend across the top shows the standard oxygen isotope stages (Peterson and Prell, 1985).

isotopic composition of a benthic foraminifer is controlled by global oceanic carbon isotopic composition, ocean circulation patterns, and average oceanic phosphate content. The use of paired analyses of carbon isotopes and cadmium provides a circulation parameter which is independent of changes in ocean chemical inventories (Boyle, 1986). Water masses can also be mapped by means of their foraminiferal assemblages. By combining these two approaches in synoptic transects for successive stages of the Miocene, Woodruff and Savin (1987) are obtaining new insights into global circulation of the Miocene ocean.

Other tracers will complement $\delta^{13}C$ - Cd/Ca studies and address different aspects of paleoceanographic change. The ^{34}S record of ocean sulphate is not yet known in detail for much of the Cenozoic (Claypool *et al.*, 1980) and is important because it bears on the mechanisms for maintaining atmospheric oxygen concentrations (Veizer *et al.*, 1980). There is a recently emerging set of new chemical data (*e.g.* Li/Ca, Sr/Ca ratios) which provide intriguing results but yet require more work before they can be fully evaluated. Radiogenic isotopes also provide important information. The use of $^{87}Sr/^{86}Sr$ ratios in stratigraphy is described below, but in addition the absolute values of the $^{87}Sr/^{86}Sr$ ratio at any one time and its change provide important constraints on the input of chemicals to the oceans from the major geochemical reservoirs (continental and hydrothermal). Furthermore, other similar tracers - Nd and possibly Pb and Os isotopes - offer the potential to further constrain these input parameters and, in the case of $^{143}Nd/^{144}Nd$ ratio, are important because of their inter-oceanic variability, thus providing the potential for charting the evolution of oceanic basins. But such investigations must be carried out only on sections that are diagenetically unaltered.

Improvements in Geochronology

Geochronology and stratigraphy define our ability to correlate events and to establish synchroneity in global environmental change. The improvements in geochronology considerably enhance the opportunities to define major changes in the climate system and to understand the important response mechanisms.

Biostratigraphy and Magnetostratigraphy. The development of a multiple biostratigraphic zonation scheme for the Cenozoic and its integration into a numerically calibrated geomagnetic polarity timescale (GPTS) (Berggren *et al.*, 1985 ; Barron *et al.*, 1985) has provided the framework for correlating Cenozoic marine and continental stratigraphies (Rögl and Steininger, 1984 ; Berggren and Van Couvering, 1984), and epicontinental and open ocean stratigraphies (Aubry, 1983, 1985, 1986). Similar studies in the Mesozoic (Kent and Gradstein, 1985 ; Van Hinte, 1976) have made it possible to place contemporary depositional stratigraphies into a unified spatial and temporal framework. In the late Neogene, global correlation has been refined by means of integrated biostratigraphy, isotopic stratigraphy, and magnetostratigraphy (Fig. 9). By integrating these stratigraphies, a resolution on the

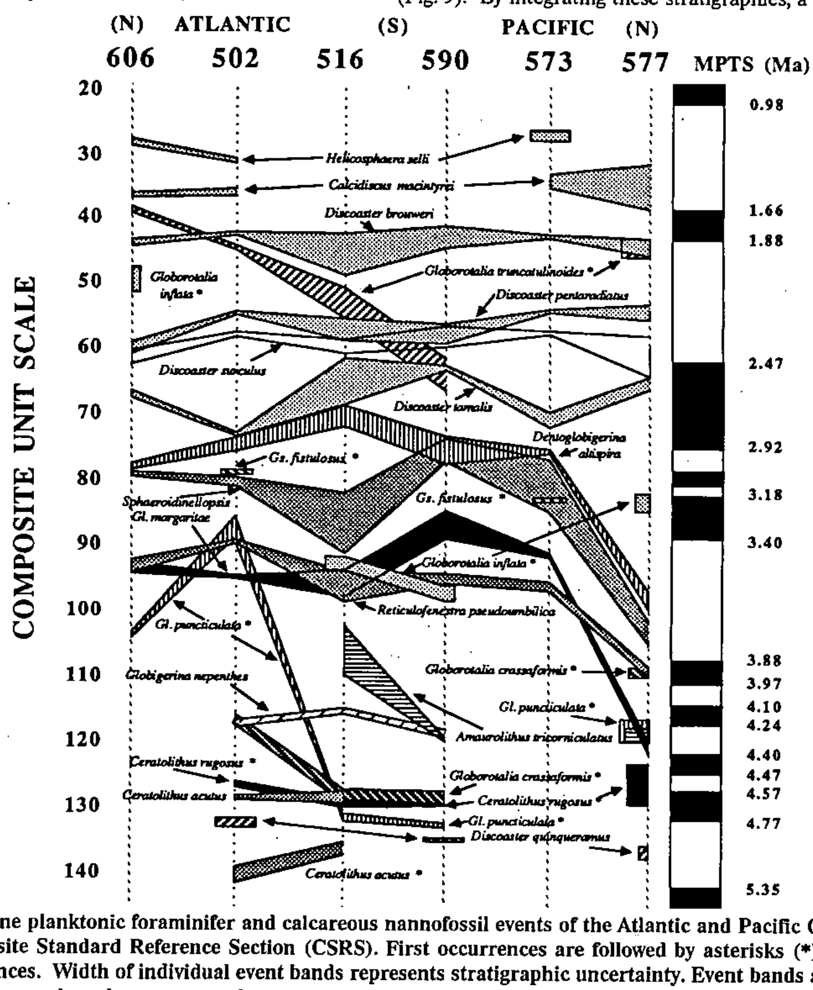

Figure 9. Pliocene planktonic foraminifer and calcareous nannofossil events of the Atlantic and Pacific Oceans displayed in units of the Composite Standard Reference Section (CSRS). First occurrences are followed by asterisks (*). Remainder of events are last occurrences. Width of individual event bands represents stratigraphic uncertainty. Event bands are shaded to aid viewing. Depths in each core have been converted to composite units. Black and white segments represent positions of magnetic reversals in the CSRS. Age (Ma) of magnetostratigraphic boundaries after Berggren, Kent and Van Couvering (1985). From H. Dowsett (1987).

order of 5000 years has been claimed for the late Pleistocene (Imbrie *et al.*, 1984) and about 100 000 years for the remainder of the Cenozoic (Moore and Romaine, 1981). Clearly, this potential can only be realized if recovery is continuous and the cores are sampled in detail.

Chemostratigraphy : Strontium. Strontium isotopes have recently been used as a supplementary tool in marine stratigraphic correlations for part of the Mesozoic and for the late Eocene to Pleistocene (Burke *et al.*, 1982 ; DePaolo and Ingram, 1985 ; Koepnik *et al.*, 1985). The ratio of strontium-87 to strontium-86 in carbonate tests of carbonate-building organisms (foraminifera, molluscs, etc.) allows the correlation of marine sediments with the standard sea-water curve and, ultimately, with a standard chronostratigraphic framework (Berggren *et al.*, 1985). Resolution of the order of 0.5 to 1.0 Ma has been recently suggested by some workers. Achieving this requires good quality carbonate sequences.

Chemostratigraphy : Isotope Events. Scholle and Arthur (1980) called attention to occasional widespread and short-term deviations of oxygen and carbon isotope ratios. These temporary anomalies find their explanation by temporary imbalances in the geochemical cycles, such as temporary excesses of carbon burial in sediments, or temporary breakdown of oceanic mixing. A number of events of this sort have been discovered in the Cenozoic, such as the Miocene Monterey Event (Fig. 10 ; Berger *et al.*, 1981), and more has been learned about old ones such as the Cenomanian-Turonian boundary (Bonarelli) event (Pratt and Threlkeld, 1984 ; Schlanger *et al.*, 1986). Such events can only be investigated in unaltered carbonate sequences.

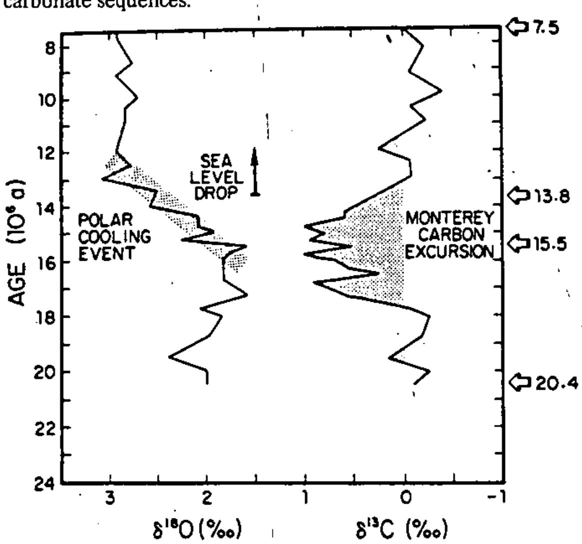

Figure 10. Stable isotope records, associated with the Miocene Monterey Event (based on the analysis of benthic foraminifera from DSDP Site 216, tropical Indian Ocean, by Vincent *et al.*, 1985). From Berger (1985).

Cyclostratigraphy from Logging. Already the Pleistocene can be geochemically zoned by the $\delta^{18}O$ fluctuations (Prell *et al.*, 1986) that reflect the growth and decay of the cryosphere in response to Milankovitch forcing (Fig. 2). The recognition of Milankovitch cyclicity throughout the record (Fischer, 1986 ; Arthur and Garrison, 1986) and the discovery of Milankovitch signatures in borehole logs (Figs. 3, 11) point to the possibility of a much more extended cyclostratigraphy with resolution in the Milankovitch frequency band (20-400 ka). To achieve this resolution it will be necessary to intensify our efforts to integrate logging measurements with core data.

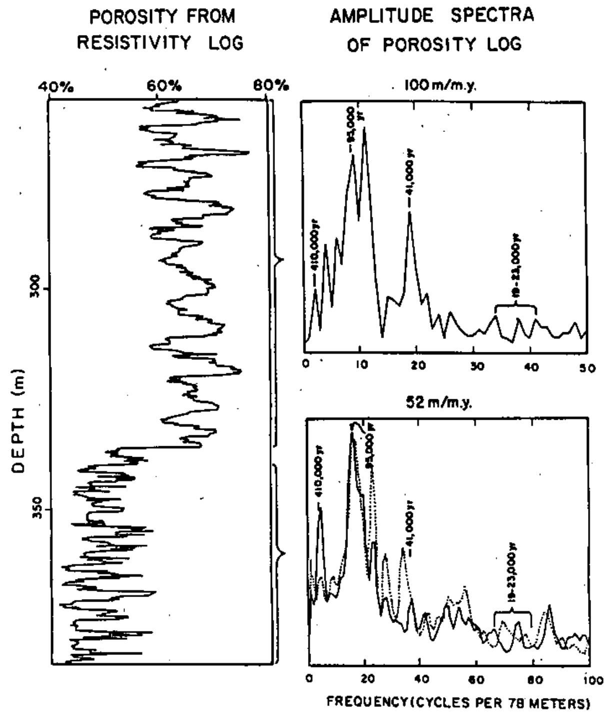

Figure 11. Porosity from electrical resistivity log, ODP Leg 105 Site 646 (left). Power spectrum from Fourier transform of porosity log above 340 m shows major energy peaks at 95 000- and 41 000-year periods (right, top). Sedimentation rates are from core paleontology. Spectra of porosity and velocity logs below 340 m show peak energy at 410 000- and 95 000-year periods (porosity log) and 95 000- and 41 000-year periods (sonic spectrum dotted). Sedimentation rate changes from 100 m/My (top) to 52 m/My below 340 m. The periods of dominant log energy are similar to cycle periods from Milankovitch climate changes. From Lamont-Doherty Borehole Research Group (1987).

Quantitative Stratigraphy. Quantitative techniques will find greater application in biostratigraphic correlation in the years ahead. While some of the basic groundwork was laid 15 to 25 years ago (Shaw, 1964 ; Hay, 1972), quantitative techniques have been little used in deep sea biostratigraphy. Notable exceptions in shallow marine Cenozoic sequences include studies by Edwards (1982a,b) and Hazel *et al.* (1984), using graphic correlation. A recent addition to this literature is a study of late Neogene interoceanic datum event correlation using forams and coccoliths by Dowsett (1986, 1987) which utilizes the same technique (Fig. 12). The use of quantitative stratigraphic correlation techniques has recently been treated in considerable detail by Gradstein *et al.* (1985). At present, we lack adequate reference sections to fully explore these methods.

Deciphering Terrestrial Climate Change

It has long been recognized that deep-sea sediments hold important clues to deciphering the environmental conditions prevailing on adjacent land areas, including the extent of glaciation, relief, weathering intensity, vegetation, erosion rates, and the nature and extent of volcanism. The following approaches illustrate some of the most promising developments.

Clay Minerals. Clay mineral provinces in the deep sea are often a continuation of clay mineral zones on the adjacent

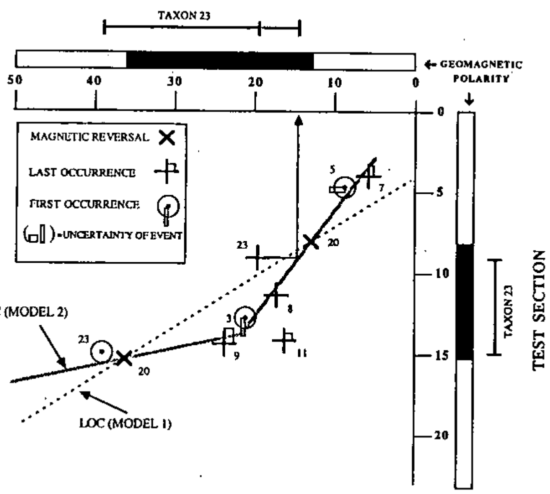

Figure 12. Graphic correlation diagram (Shaw plot) of hypothetical biostratigraphic and magnetostratigraphic data. Standard Reference Section (SRS) on horizontal axis, Test Section on vertical axis, both scaled as depth in core. Stratigraphic range of taxon 23 is plotted along both axes as a bar. First and last appearances of species are plotted as points (first occurrences : circle ; last occurrences : cross) on graph. Magnetic reversal boundaries identified in both cores are plotted as "X" on graph. Assumed true line of correlation (LOC) is drawn through isochronous points.LOC model 1 based solely on geomagnetic reversal data ; LOC model 2 (the preferred model) based on both geophysical and paleontological data. Note that the projected position of fossil events in the SRS varies depending upon which LOC model is used. Last appearance of taxon 23 occurs earlier in SRS than Test Section so that its range is revised accordingly in SRS. No other revisions can be made to lengthen ranges in SRS. The break in slope of the LOC (model 2) indicates that a relative change in rate of rock accumulation has taken place. In this diagram the sampling uncertainties are indicated by a rectangle of appropriate size (Dowsett, 1987).

continent. Since, during rock weathering, minerals undergo changes controlled by humidity, temperature and drainage, the record of clay mineral variations in the deep sea can shed considerable light on the climate and relief within the adjacent continental drainage basins (Chamley, 1979, 1981). More subtle variations in clay mineral chemistry, shape and crystallinity can also be used to identify local changes in continental climate. For example, the iron content and crystallinity of chlorite are inversely related to temperature and humidity. Illites undergo a decrease in potassium and crystallinity with increased intensity of chemical weathering. Recent advances in the use of scanning electron microscopy of clays, improved microprobe analysis of single particles, the increased use of transmission electron microscopy, the development of scanning transmission electron microscopy for clays (*e.g.* Colliex and Treacy, 1983) and the application of various isotopic methods (*e.g.* $^{87}Sr/^{86}Sr$) to clay mineral work will undoubtedly permit more precise determinations of source, environmental conditions and transport history of clays in the deep sea. Careful site selection to recover the record of critical continental environments is required.

Terrestrial Organic Components. Various terrestrial organic materials survive transport to continental margins and abyssal plains, and provide some of the most specific indications of soil conditions, and hence terrestrial relief, drainage and climate (*e.g.* Groot and Groot, 1966). Refinements in the extraction and classification of pollen, fungal spores, phytoliths, fresh water diatoms and other refractory plant components will lead to more detailed interpretations of vegetation and climate.

Recent advances in organic geochemical analysis also offer great promise. Biomarkers, highly resistant organic molecules, can be identified in samples as small as a few nanograms and can often be related quite precisely to particular sources and indirectly to particular environmental conditions (Brassell *et al.*, 1986 ; Curry, 1987). Clearly, sediments that are not oxidized contain the best organic records.

Eolian Transport. Much of the non-biogenic sediment accumulation beyond the region of hemipelagic deposition is composed of quartz and clays delivered by wind. The distribution of such material in recent sediments reflects present-day atmospheric circulation. Thus, variation through time in the distribution, accumulation rate, grain size and composition of the eolian component of pelagic sediments (Fig. 13) have been used to infer changes in wind intensity, zonal wind patterns and continental climate (*e.g.* Rea *et al.*, 1985). Cores must be sited to sample the major paleo-wind belts.

Tectonic Uplift. Hay's (1987) work in modeling the topography and uplift rates of continents from the volume of marine sediment is discussed below. Good calibration of seismic stratigraphy is required to apply these models.

Evidence for Major Changes

The presently available evidence for major changes in the ocean environment is sufficient to describe major events and trends. These data define the major problems for which extended investigation has the potential to lead to major advances in our understanding of climatic change and climate sensitivity. Although the text below discusses physical and chemical changes separately, the two types are often coupled.

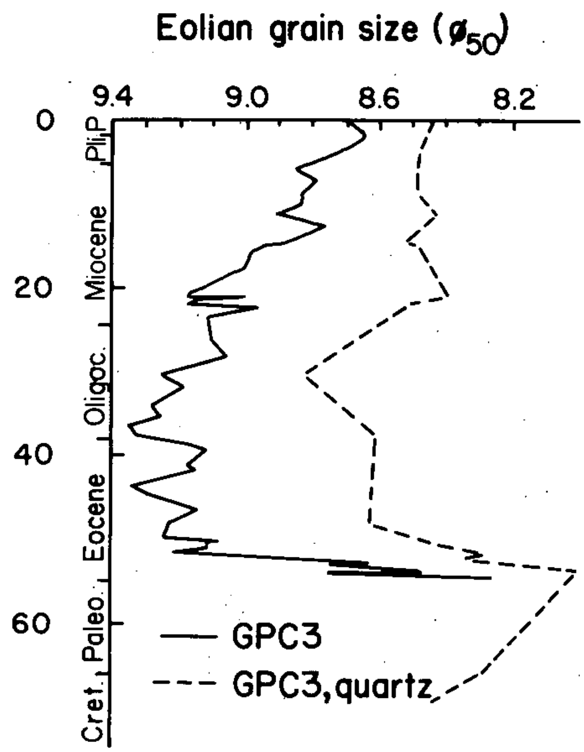

Figure 13. Eolian grain-size distribution for quartz and for total sediment in core GPC3 in the Central Pacific Ocean from the Pleistocene to the late Cretaceous (Rea *et al.*, 1985). Age in Ma.

Physical Changes. Major climatic and oceanic events and trends have been identified, though the explanations of the phenomena remain speculative. For example, the concept of a reversed deep-sea circulation, with large-scale formation of warm deep waters in the paratropical belts, suggested long ago by Chamberlin, is now finding observational support in the studies of Miocene foraminiferal faunas of intermediate depth (Woodruff and Savin, 1987). Have the oceans undergone many such flip-flops in circulation mode ? Also puzzling are the longer global episodes of oceanic susceptibility to anoxia (Schlanger and Jenkyns, 1976), and times of widespread oceanic silica accumulation. Equally puzzling are shorter, isotope-delineated events such as the Cenomanian-Turonian (Bonarelli) event (Schlanger *et al.*, 1986) and the Miocene Monterey Event (Fig. 10 ; Vincent and Berger, 1985) that suggest transient division of the global ocean into separate reservoirs, or temporary excessive storage of organic carbon in the atmosphere. Intriguing is the possibility that climates have responded throughout time to the earth's orbital cycles. The hundreds of individual short anoxic events recorded in the Atlantic Cretaceous (Arthur and Dean, 1986) appear to be orbitally related. In the Italian Albian, mid-Cretaceous carbonate productivity and bottom redox-cycles (Fig. 3) ran in tune with (orbital) precessional and eccentricity cycles (Herbert and Fischer, 1986). The obliquity cycle seem more commonly expressed in variations of detrital flux (Fischer, 1986), raising the problem of whether even in Cretaceous time there was a small ice-cap that gave rise to minor eustatic cycles. These and other emerging observations provide important individual targets for inquiry.

An example of a fundamental change in Cenozoic paleoceanography is the destruction of circumglobal low-latitude circulation. Loss of equatorial circulation coincided, in general, with the development of the circum-Antarctic circulation system as southern land masses moved away creating unrestricted latitudinal flow (Fig. 14). The history of Antarctic circulation is central to the study of global climate and circulation (Kennett, 1977, 1978). The formation and later development of the circum-Antarctic current had the effect of thermally isolating Antarctica by decoupling warmer subtropical gyres from the Antarctic Continent (Fig. 15). These warm gyres migrated progressively northwards as the cold circum-Antarctic Current increased in width. This, in turn, led to the development of increased Antarctic glaciation and later ice-sheet formation, a climatic regime which itself had a major effect on the environmental and biogeographic evolution at high southern latitudes. Environmental characteristics resulting from the development of this climatic regime included extensive seasonal sea-ice production, cooling of waters suurrounding the continent, and meteorologically-forced upwelling of nutrient-rich intermediate waters which increased biogenic productivity in the Southern Ocean. The thermal barriers in high southern latitudes represented by the Antarctic Convergence and Subtropical Convergence also became major planktonic biogeographic barriers. ODP Leg 113 found evidence of sequential cooling of Antarctica and surrounding oceans during the Cenozoic that profoundly affected the sediments and the biota. Glacial development probably began during the late Paleogene in East Antarctica and during the Neogene in West Antarctica (Barker, Kennett *et al.*, 1987).

Diverse calcareous microfossil and clay mineral assemblages reflect the relative warmth of the surface and bottom water masses adjacent to Antarctica during the Late Cretaceous through the Eocene. An Eocene palynoflora indicates the presence of temperate beech forests with an undergrowth of ferns on the northern Antarctic Peninsula. Although both the Cretaceous and the Eocene are characterized by considerable evidence for polar warmth, the two climates were apparently very different. Eolian sediment data suggest much weaker winds during the Eocene (Rea *et al.*, 1985) and some interpretations of the oxygen isotopic data (Shackleton and Boersma, 1981) suggest the possibility that Eocene tropics were much cooler than today or than during the Cretaceous. These differences, if real, would demand very different mechanisms to maintain polar warmth. Events such as the widespread mid-Eocene deposition of chert also present an intriguing problem in the light of silica deposition in the modern ocean.

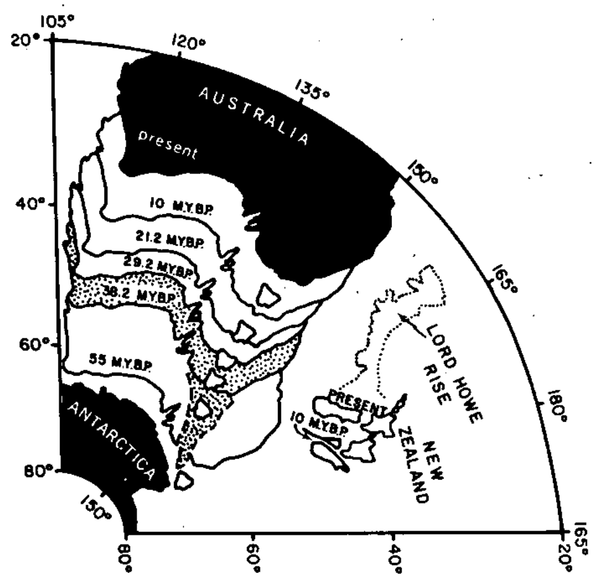

Figure 14. Successive positions of Australia relative to Antarctica as Australia moved northward during the Cenozoic. The position of Australia at 38 Ma (Eocene-Oligocene boundary) is shown (stippled) to include the South Tasman rise, which is of continental crust and which prevented the development of deep circum-Antarctic circulation well after spreading commenced (Weissel and Hayes, 1972 ; Kennett, 1977).

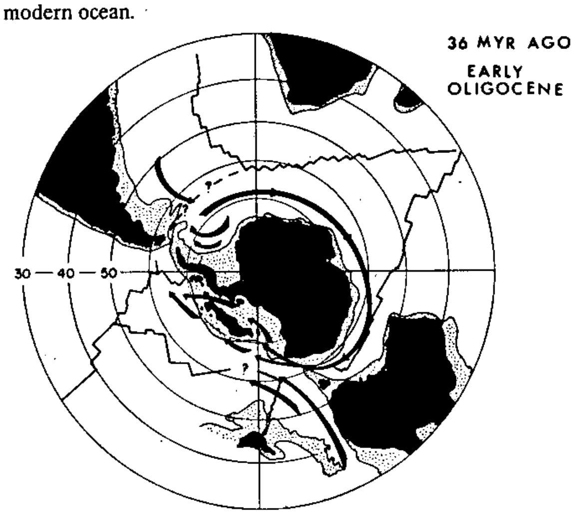

Figure 15. Reconstruction of the Southern Ocean and suggested surface-water circulation (heavy arrows) during the earliest Oligocene 36 Ma. A substantial ocean has now formed between Australia and Antarctica, although the southward extension of the continental South Tasman rise and Tasmania continued to block deep circum-Antarctic flow between these two continents. The Drake Passage remains closed between South America and Antarctica. A shallow, surface-water connection is by this time established over the South Tasman rise, leading possibly to cooling and sea-ice formation in the Ross Sea region (Kennett, 1978).

On Maud Rise, clay minerals support isotopic and biogeographic data for global cooling at the beginning of the Oligocene. A minor ice build-up is suggested for eastern but not for western Antarctica. No evidence was found for major ice build-up during the Oligocene. The presence of ice-rafted debris (IRD) in a site closely adjacent to East Antarctica indicates the existence of some ice on East Antarctica during the late early Oligocene, the earliest detected during Leg 113.

A further step in Antarctic evolution occurred during the middle Miocene. The middle Miocene is missing in a hiatus in a site off east Antarctica (Site 693), and a noticeable increase occurs in the abundance of IRD in the lower upper Miocene sediments immediately above. A significant cooling probably also occurred during the middle Miocene in West Antarctica. Here, strong physical weathering, inferred to have resulted from climatic cooling, developed much later than in East Antarctica. The continued absence of IRD through the middle and early late Miocene suggests, however, that major glaciation might not yet have begun on West Antarctica.

Leg 113 data suggest that once East Antarctica was ice-covered, it did not undergo significant deglaciation, even during the early Pliocene. The data also indicate that the West Antarctica ice-sheet probably did not begin to form until the late Miocene. It may have been unstable during the early stages of its development, but became stable in the earliest Pliocene at about 4.8 Ma.

Chemical Changes. Stable isotopes in calcareous fossils, carbonate accumulation in the deep sea, and organic matter deposition, provided a basis for documenting changes in the chemical state of the ocean (Hsü and Weissert, 1984; Sundquist and Broecker, 1985). Most of the physical changes described in the paragraphs above have also been described as chemical changes and chemical events. Certainly, the chemical system is intimately linked to the physical system and chemical signatures are a major element in defining environmental change. A number of examples of a changing chemical system can be added to the evidence for trends and events in addition to the examples outlined previously.

The carbon isotope record in deep-sea sediments deposited on the ocean floor during the past 100 000 000 years can be interpreted in terms of the history of the partitioning of carbon between reduced and oxidized, *i.e.* in terms of the burial of organic carbon. Shackleton (1985) inferred a reduction by about 10^{19} moles over the last few tens of million years, drawing down the atmospheric oxygen content from 0.25 atmosphere to its present 0.2 atmosphere. More recently, Kump and Garrels have refined this estimate taking into account the sulphur cycle, but not modifying the major implication that the atmospheric oxygen level must be regarded as a geological variable over relatively short intervals. The history of carbon isotope gradients within the ocean, recorded in the carbon isotopic content of benthic and planktic foraminifera, constrains the upper limit on the ocean ΣCO_2, a critical constraint on models such as that of Berner *et al.* (1983) or Lasaga *et al.* (1985). Taken together with data on carbonate preservation/dissolution, and data on Cd/Ca, carbon isotope information will permit us to determine the history of ocean carbonate chemistry and hence to calculate the history of atmospheric CO_2, building on the work of Broecker (1982) and of Shackleton and Pisias (1985).

The reconstruction of the stable isotope record has progressed from generalized temperature curves (Savin *et al.*, 1985) to comparisons of trends for different depths and between different ocean basins. Yet attempts at quantifying ocean chemistry changes in Tertiary oceans are still at the beginning. Vincent and Berger (1985) used a simple input/output model to argue that large-scale extraction of organic matter 17 million years ago set the stage for subsequent cooling and ice build-up in the Antarctic. In this model, the carbon extraction occurred around the rims of the Pacific mainly, into upwelling-influenced sediments which today are source rocks for hydrocarbon (Monterey Formation and equivalent deposits). The deep-sea signal allowing a correlation of margin and open ocean deposits is the $\delta^{13}C$ record of foraminifera. Their work raises the question just how the past CO_2 of the atmosphere is to be reconstructed. Since both total CO_2 and alkalinity are necessary to do this, one needs detailed information both on $\delta^{13}C$ gradients and on saturation levels (lysocline and CCD).

The largest benthic $\delta^{13}C$ shift occurred within the late Paleocene (Shackleton, 1986) and has been interpreted in terms of variability in productivity. The late Paleocene is also associated with major taxonomic turnover among benthic foraminifera and significant changes in sea floor spreading rates (Berggren *et al.*, 1985).

Some Cretaceous events (*e.g.* the Bonarelli event) are now well defined global chemical features. However, in other cases the reconstruction of trends and events lags considerably behind similar efforts in the Tertiary, for several reasons. First, there is a less satisfactory coverage of the record, and second, there is the strangeness of the pre-ice-age system. Volcanic outgassing of acids is emerging as an important topic in connection with the peculiarities of the history of the Cretaceous carbon cycle and the associated climate. Catastrophic outgassing has been invoked in connection with the End-of-Cretaceous event (McLean, 1985), in the ongoing controversy on this period of mass extinction. The study of this period has also greatly stimulated stratigraphic research into impact phenomena, with detailed work on deep-sea sediments playing a central role.

The Observational Challenge. The extent to which we understand ancient climates and oceans is inversely proportional to their age, for two reasons. As we go back in time, the global configuration becomes less and less like the one we live in. At the same time, the database becomes smaller in both quantity and quality : smaller in quantity because there are fewer long cores than short ones and lesser in quality because time and burial both contribute to diagenetic alterations. In comparing work on the Pleistocene ocean with work on the Eocene ocean, for example, the former offers a much greater number of cores obtained at smaller expense, a much better time resolution, and little diagenesis - but provides view of a world much like our own. In the Eocene, information is harder to come by and is of lesser quality, but the climate with its very warm Arctic poses riddles of a high order. The following paragraphs illustrate this point.

Miocene. The resolution obtainable in Miocene studies is midway between those of the Pleistocene and of the Paleogene. Much detail on the Miocene ocean is to be found in the CENOP volume (Kennett, 1985), and in studies which grew from this effort. Particularly noteworthy is Woodruff and Savin's (1987) study of Miocene circulation patterns. In this study, a biogeography of oceanic benthic foraminiferal assemblages was combined with a study of their carbon-isotope ratios. Subject to some corrections, ^{13}C should be a relative measure of the age of deep water masses, gradients in this value should indicate direction of water movement, and successive maps or transects of the oceans should then provide insights into the patterns and history of oceanic circulation. Due to the CCD there is no information on truly deep waters, but the transects produced indicate major changes in the origin of the intermediate water masses, formed at some times in high latitudes, but at others in the low latitudes of the Indian Ocean, spreading the Indian Ocean foraminiferal fauna around the globe.

Such transects, calling for the mapping of geographic gradients at successive time slices, depend on the combination of continuous HPC/XCB cores, and arrays of drill sites over a range of paleodepths. Since significant gaps are present in our present coverage, an organized program of drilling is needed.

Paleogene. The Paleogene stratigraphic record recovered by ocean drilling is surprisingly limited in its suitability for reconstructing global oceanographic changes. Coverage is limited by incomplete records due to hiatuses, drilling gaps, and core disturbances, and by poor stratigraphic control, diagenetic alteration of most deeply buried sections (>500 m burial depth), and slow sedimentation rates. The problem of diagenesis versus sedimentation rate is particularly acute when dealing with older Paleogene strata, for in high sedimentation rate areas the overburden results in diagenetic alteration, rendering sections unsuitable for many paleoenvironmental reconstructions. Major gaps exist in our stratigraphic and geographic coverage of the Paleogene. For example, the Paleocene-lower Eocene Pacific carbonate record is represented at only one site (577), while there is no suitable middle Eocene Pacific carbonate record in low latitudes.

The best results have been obtained from HPC coring on the flanks of oceanic rises (Legs 72 to 74). These yielded good paleomagnetic chronologies, and the stable isotope data from them (Shackleton *et al.*, 1984 ; Oberhänsli *et al.*, 1984 ; Poore and Matthews, 1984 ; Miller *et al.*, 1987) have provided the beginnings of a Paleogene paleoceanography. Serendipity has played a role in obtaining good Paleogene records. For example, although designed primarily for hard rock drilling, Leg 82 obtained the best Oligocene North Atlantic records available by punching holes along an isochron of the mid-Atlantic ridge flank. Other DSDP/ODP legs have obtained relatively complete Paleogene sections, but they suffered from uncertain paleomagnetics or from diagenetic alterations due to deep burial.

Reconstructing the Paleogene ocean remains an important challenge, especially because large changes occurred in the ocean-climate system during this interval. For example, the early Eocene may provide our best analogue for understanding the grand experiment of high anthropogenic CO_2 levels. In order to reconstruct Paleogene climatic and oceanographic fluctuations, we require a network of suitable cores from every ocean basin, providing diagenetically unaltered sections with paleomagnetic control and high sedimentation rates. These criteria limit the areas that are suitable. However, experience has shown that the flanks of oceanic rises have yielded excellent results. The importance of paleomagnetic control on sections obtained for such global oceanic reconstructions cannot be overemphasized ; in particular, reconstructions of the climatically critical equatorial areas require reliable horizontal orientations for obtaining a paleomagnetic stratigraphy. With complete, well-constrained sections, reconstructions of the Paleogene oceans will unlock important ocean-climate changes, including the transition from an ice-free to a glaciated world.

Improvements in Modeling

Atmospheric Circulation. Improvement in the development of quantitative models of the climate system has been dramatic over the last five years. Comprehensive three-dimensional models of the atmosphere, oceans, sea-ice and the cryosphere have been developed with wide applications (Washington and Parkinson, 1986). Although many of the applications have considered these components of the climate system independently, the current frontier involves the major interactions between the ocean, atmosphere and ice. The applications of climate models also include a growing inventory of paleoclimatic studies from ice-age simulations (*e.g.* Manabe and Broccoli, 1985) to simulations of orbitally-induced changes in the hydrologic cycle (Kutzbach and Guetter, 1986) to investigation of the role of paleogeography in explaining Cretaceous warmth (Barron and Washington, 1985).

These mathematical models provide the opportunity to address the problems of cause and mechanism in climatic change. A unified approach to this problem weds comprehensive observations and models based on physical and chemical principles which are largely independent of the data used to characterize trends and events in global change. The purpose of models is to replace the complex natural system by a simplified but more formal statement of our knowledge, which can then be applied to gain insight, to identify important processes, to evaluate hypotheses and to identify areas of further study.

Improvements in models over the last decade and the increased application to paleoclimatic problems have led to a number of interesting perspectives. For example :

(1) The wind intensity and wind stress applied by the atmosphere to the ocean surface can be related to the vertically integrated meridional temperature gradient in the atmosphere. Because of the importance of the non-linear saturation vapor pressure relationship with surface temperature and the role of condensation in atmospheric heating, changes in tropical sea surface temperature are a primary control of the meridional temperature gradient. For a Cretaceous case with very warm poles and a 2°C increase in tropical temperatures the zonal atmospheric winds will be as strong as today. In an Eocene interpretation with warm poles and cooler tropics the reverse occurs and the role of wind stress in the ocean circulation will be reduced (Fig. 16).

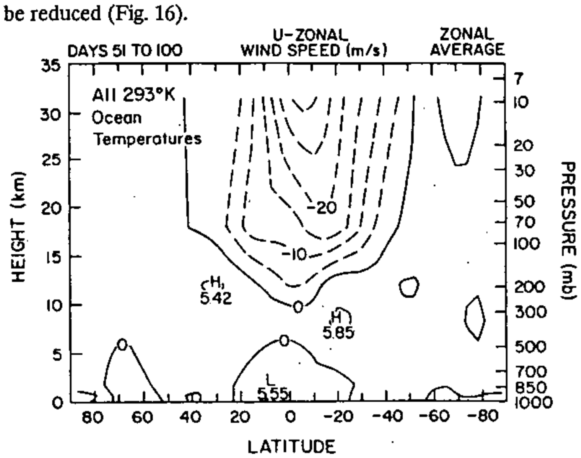

Figure 16. The zonal winds with respect to latitude for a Cretaceous sensitivity experiment with instantaneous ocean mixing (uniform 20°C) using a general circulation model of the atmosphere. Note the lack of the familiar mid-latitude jets which today are on the order of 30 to 40 m/s (Barron, 1986).

(2) A physical argument can be presented which suggests that wind patterns must have been different in the past. Because energy and angular momentum balances maintain the atmospheric circulation, different frictional torques exerted over land and sea and associated with topography imply that different continental and topographic distributions must alter the exchanges of angular momentum between the surface and the atmosphere, and hence the atmospheric motions which maintain the angular momentum balance. The potential importance of geography as an influence on the global circulation is illustrated in a series of sensitivity experiments using a general circulation model of the atmosphere with a simple energy balance ocean and mean annual solar insolation. Model experiments were completed for the present day, and for assumptions of flat or mountainous and high or low sealevel continents. Figure 17 shows the large differences in surface pressure patterns due to geography assumptions. These differences are extreme enough to change

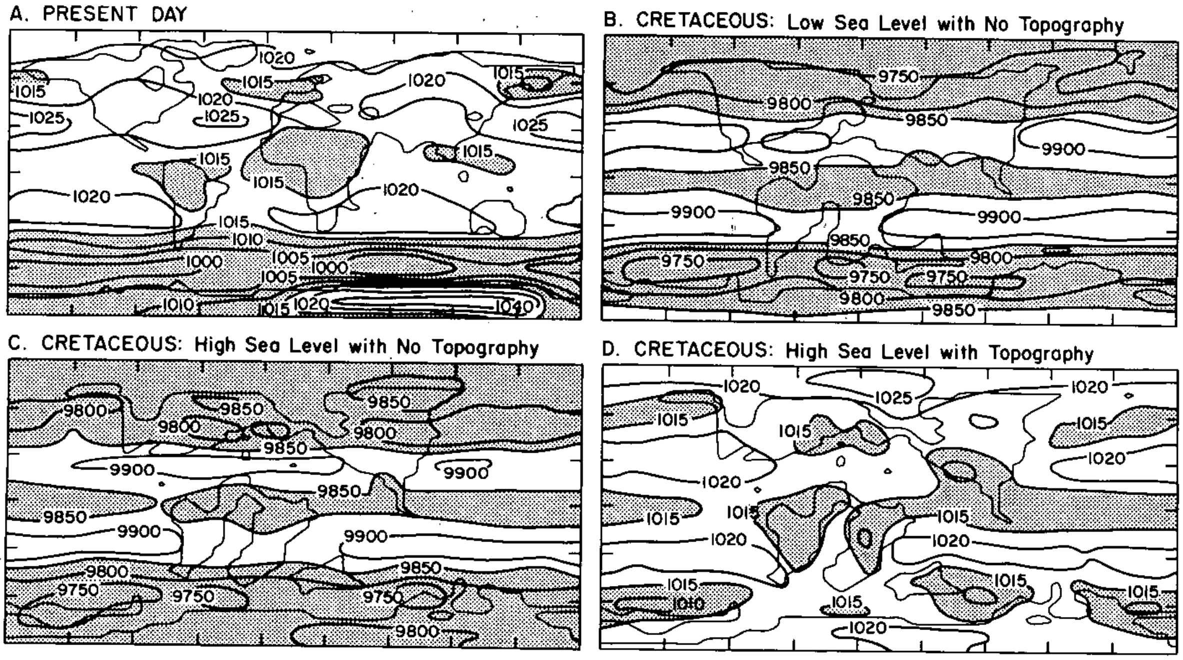

Figure 17. A comparison of surface pressure predictions for mean annual simulations for (A) the present day, (B) Cretaceous low sealevel with no topography, (C) Cretaceous high sealevel with no topography and (D) Cretaceous high sealevel with topography (Barron, 1986).

the sign of the mean winds at high latitudes. Conversely, the low-latitude circulation appears to be fairly stable. Evidently, topography is an important variable for the ocean circulation, at least from the viewpoints of as yet limited experiments.

(3) The role of salinity contrasts and the variability in sources of saline and fresh water may have had a substantial impact on the ocean circulation. A number of model studies indicate variations with respect to geometry (zonal subtropical Tethys and very high marginal precipitation), monsoonal changes with variations in the earth's orbit, and potential changes in the global hydrologic cycle with planetary warming or cooling.

An Eocene example will illustrate the potential of models in a unified, experimental approach to global environmental change : The majority of past climates over the last 100 million years show evidence that global warming or cooling is accompanied by a temperature change of similar sign at every latitude. In contrast, Shackleton and Boersma (1981) present oxygen isotopic evidence that Eocene oceans were cooler in the tropics, but substantially warmer at the poles than at the present day (Fig. 18). These data from ocean drilling are provocative. First, climate models (*e.g.* Stone, 1978 ; Manabe *et al.*, 1975) suggest that a greater poleward heat transport (as implied by these data) is enigmatic, and that ocean and atmospheric heat transport are compensating in maintaining the total poleward heat transport. If the Eocene isotopic data are then interpreted as the result of a greater ocean heat transport, the consequences are a weaker atmosphere and greater seasonal temperature contrast (*i.e.*, colder winters in the absence of a strong atmospheric circulation) in continental interiors (Schneider *et al.*, 1985). This purely deductive model prediction is partially confirmed and partially denied by independent data. The particle size of eolian sediments (Fig. 13) in the deep sea apparently represents a drastic drop in Eocene zonal wind speed in the atmosphere (Rea *et al.*, 1985). However, paleobotanical data from continental interiors have been interpreted as indicating a much reduced amplitude of the seasonal cycle (MacGinitie, 1974). Any solution to this enigma has important implications. The solutions may include new

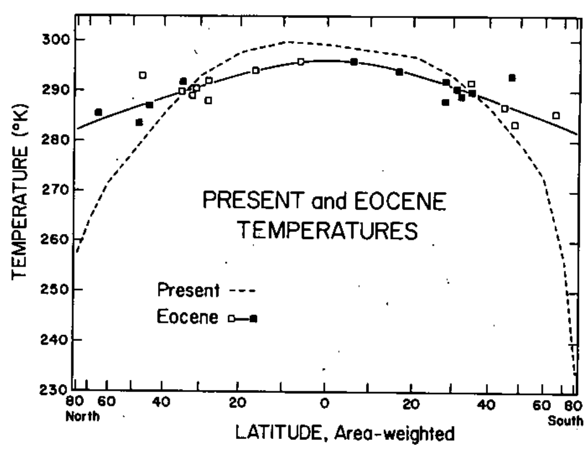

Figure 18. Isotopic paleotemperatures of the Eocene surface ocean from Shackleton and Boersma (1981) in comparison with modern values. Northern and southern hemisphere isotopic values are plotted in both hemispheres (mirror data sites are plotted as empty squares) in order to draw a temperature distribution with respect to latitude. The latitude scale is area-weighted.

mechanisms (the mechanism for an increased role by the oceans is unknown or uncertain) or a re-analysis of either model capability or one or more of the sources of data (eolian sediment, oxygen isotopes or paleobotany) or the potential of alternative causes of climate change. In any case, a unified approach has the potential of revolutionizing our understanding of the climate system and how it has been recorded.

Ocean Circulation and Chemistry. In the application of ocean models to paleocean chemistry problems there is a natural division between processes of "redistribution" and "mass balance". Processes of redistribution can change the chemical partitioning of important chemical species within the ocean by changes in ocean circulation or biological transport. Changes in ocean chemistry produced by redistribution can occur quite rapidly relative to changes in the forcing functions. The chemical mass balance of the ocean, on the other hand, is maintained on timescales relevant to continental weathering and sediment burial. A convenient benchmark might be the residence time of carbon in the ocean (100 000-200 000 years). Thus environmental changes which occur over the low frequency Milankovitch cycles may include elements of the ocean's chemical mass balance, whereas the high frequency cycles and events are dominated by ocean chemistry changes which are independent of the mass balance. This distinction is important in evaluating the development of models for the ocean's chemical system.

By the time the recommendations of COSOD II take effect, three-dimensional models of ocean circulation will be running that include the important chemical tracers (nutrients, ΣCO_2, and alkalinity) and biological transformations. Such models should be capable of exploring the redistributional components of ocean chemical change in response to simple changes in surface forcing. A few years hence, fully coupled ocean-atmosphere circulation models with ocean chemistry should be available for exploring the response of the whole system to quite realistic representations of external forcing, including orbitally-induced insolation changes and continental-geometry changes. At the present time, ocean chemical models are limited to chemical box models in which features of the ocean circulation and biology are highly simplified idealizations of reality.

Figure 19 shows a north-south section of the zonally-averaged meridional circulation of the ocean as realized in the three-dimensional GFDL world ocean model (Bryan and Lewis, 1979). The equatorial upwelling cells in the upper 200 m, the North Atlantic Deep Water flow pushing southward near 2000 m, and the Antarctic Bottom Water flow pushing northward at the bottom are notable and familiar features. Of most importance to the partitioning of carbon between the ocean and atmosphere, however, is the deeply-penetrating counter-clockwise cell in the circumpolar region. The southern ocean is a unique oceanic region because a gap exists between South America and Antarctica which allows a continuous zonal circulation. The lack of a continuous continental barrier disrupts the geostrophic balance between the east-west pressure gradient and the Coriolis force which prevails to the north of the gap. This prevents a poleward flow of water across the gap near the surface and leads to downwelling on the equatorward side of the gap (Gill and Bryan, 1971). The deep circumpolar cell is extremely important in the present context because it isolates surface waters south of the circumpolar region from surface waters in the rest of the ocean. Present day Antarctic surface waters acquire their hydrographic and chemical properties from deep water masses below. Because such a large fraction of the deep ocean's volume communicates with the atmosphere through the Antarctic, Antarctic surface water acts as the major conduit for CO_2 exchange between the deep ocean and atmosphere.

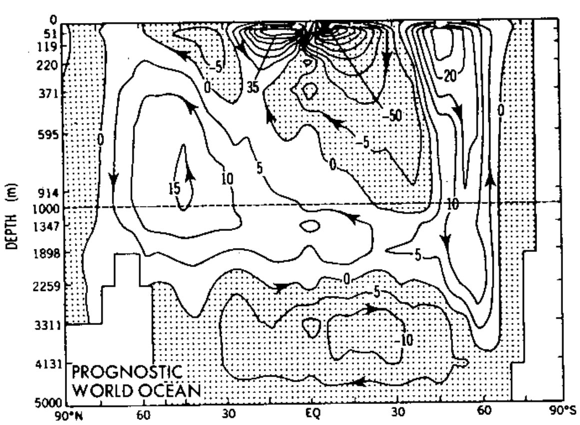

Figure 19. Overturning circulation of the world ocean in a meridional plane averaged across Atlantic, Pacific, and Indian Oceans, as realized in the three-dimensional ocean circulation model of the Geophysical Fluid Dynamics Laboratory, Princeton. Units of flow are in Sverdrups (10^6 m^3/s) (Bryan and Lewis, 1979).

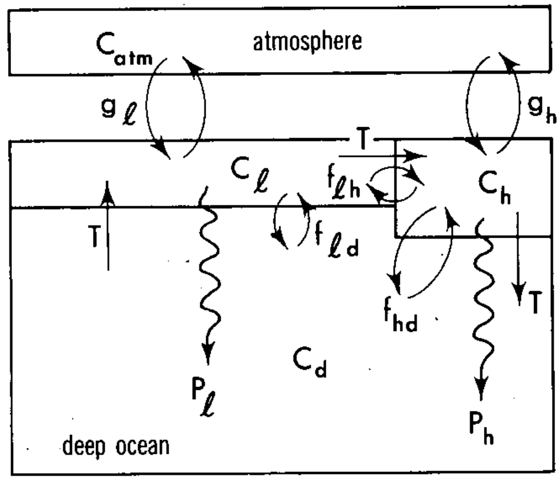

Figure 20. Chemical box model of the world ocean representing low latitude surface ocean, C_l; high latitude surface ocean, C_h; and deep ocean, D_d. Flux T represents the thermohaline circulation of the ocean. Fluxes f_{ld}, f_{lh}, and f_{hd} represent bi-directional mixing terms between ocean reservoirs. Fluxes g_l and g_h represent gas exchange of CO_2 between surface ocean and atmosphere. Fluxes P_l and P_h represent biological transport of organic carbon, $CaCO_3$, and phosphate (Toggweiler and Sarmiento, 1985).

The 3-D model's realization of the circulation patterns of the southern ocean have been idealized in a chemical box model (Fig. 20). Several authors have hypothesized that changes in the local convective exchange between surface water and deep water and/or the local uptake of nutrients and CO_2 by the biota produced a sufficient alteration of Antarctic surface water properties to explain the 80 ppm rise in atmospheric CO_2 at the close of the last ice age. The atmospheric CO_2 content in ppm predicted by the box model has been plotted in Figure 21 as a function of the primary flux terms. The model's atmospheric CO_2 responds dramatically to changes in f_{hd}, the local surface to deep box exchange rate (vertical axis). Model sensitivity to the T flux, or ocean-wide thermohaline overturning, is much smaller.

Models of the ocean's chemical mass balance are at an earlier stage of development. However, these models are already contributing a number of important hypotheses on the ocean-atmosphere chemical system. A notable example is the BLAG model (Berner *et al.*, 1983 ; Lasaga *et al.*, 1985). The BLAG model represents the ocean as a single box in which ocean chemical properties are not differentiated. Losses of $CaCO_3$, $MgCO_3$, organic carbon, or Fe, from the ocean are dependent on average chemical properties only. In reality, these losses occur in specialized environments within the ocean which are defined by redox state and pH. Improvements in mass balance models await the development of more sophisticated box models and perhaps full circulation models which differentiate between surface water and deep water and predict deep-sea oxygen concentrations.

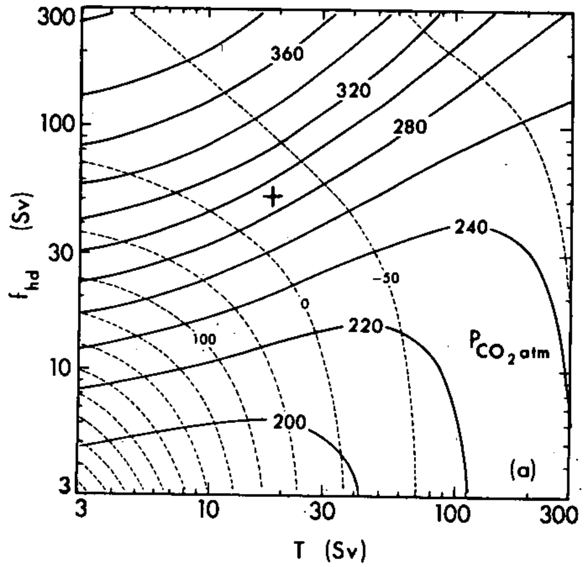

Figure 21. Atmospheric partial pressure of CO_2 (bold contours) predicted by the chemical box model (in ppm) as a function of fluxes f_{hd} (vertical axis) and T (horizontal axis). Steady state solutions of the model are computed for 440 combinations of f_{hd} and T over ranges from 3 to 300 Sverdrups and the results contoured. Dashed contours represent predicted atmospheric ^{14}C content in Δ notation (per mil) (Toggweiler and Sarmiento, 1985).

Ice Sheets. Recent progress in modeling the Antarctic ice sheet has clear implications for investigations of climatic and sealevel history. For example, Oerlemans (Oerlemans, 1982 ; Oerlemans and Van der Veen, 1984) has developed a model which calculates the thickness of the East and West Antarctic Ice Sheets, and the extent of ice shelves, given sealevel and the atmospheric temperature at sealevel. Athough this effort must be regarded as preliminary, and some of the modeling assumptions must be tested with care, his results nevertheless demonstrate the difference between drawing conclusions on the basis of simple intuition (cold ocean = big ice sheet) and on the basis of numerical calculations from fundamental physical principles. Oerlemans' experiments (Fig. 22) suggest the possibility that a 9°C warming of the Antarctic Ocean might lead to thicker ice in central portions of the East Antarctic Ice Sheet ; and that substantial ice caps would remain on parts of the continent with an additional warming of 5°C and even 10°C. This argument, taken in conjunction with field evidence that the East Antarctic Ice Sheet was larger than today during some pre-Pleistocene phase (Denton *et al.*, 1984), makes it abundantly clear that future efforts to improve our knowledge of the history of sealevel and climate must involve an experimental effort in which the results of ODP drilling and Antarctic field work are integrated with modeling.

Land Elevations. Mass-balance modeling of sediments in a topographic system of sources and sinks is a new and promising paleotopographic method recently developed by Hay and his colleagues (Hay *et al.*, 1987). Required data inputs to the model are (1) an average stratigraphic column and present-day elevation for each gridpoint in the system, and (2) information on sealevel changes. The major assumptions involved are that erosion rates are primarily a function of elevation, sediment type, and age of outcropping rock ; and that erosional processes are much slower than tectonic movements. Sediment deposited during a given time interval (shaded area on Figure 23) is converted to mass by removing porosity and autochthonous material, and redistributed about the source

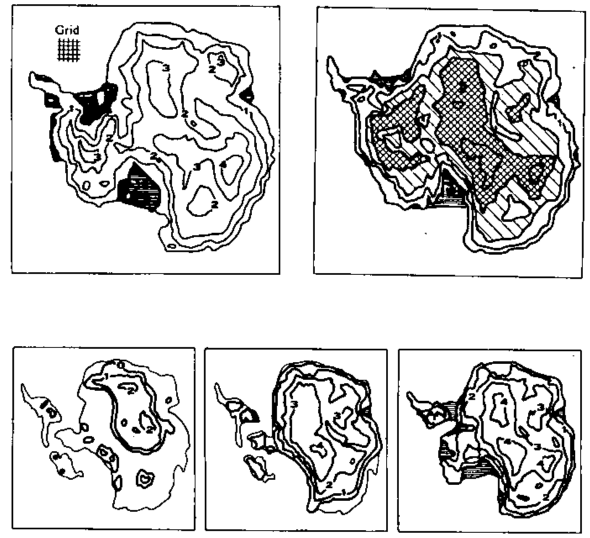

Figure 22. Observed and modeled Antarctic Ice Sheet. A : Observed ice thickness as resolved on the model grid. Contour interval is 1 km. Major ice shelves shown by shading. B : Equilibrium state of the ice sheet computed by a numerical model for present sealevel and an atmospheric sealevel temperature of -14°C. Light and heavy shading indicates ice thickness over 2 km and 3 km. C, D, E : Equilibrium states of the model ice sheet for annual sealevel temperatures of 5°C, 0°C, and -5°C, respectively. Note that an increase in sealevel temperature from -14°C to -5°C results in thicker ice in parts of East Antarctica ; and that substantial ice caps are calculated by this model for warmer conditions (Oerlemans, 1982).

area based on the inverse of modern erosion models. Shoreline and drainage divide locations are not inputs, although their positions are estimated by the model. Surfaces in the sediment source-sink system respond to (1) isostatic depression due to loading (*e.g.* sediment, pore fluid, sea water), (2) isostatic uplift due to unloading, (3) addition of bulk sediment, (4) loss of bulk sediment, (5) sealevel changes, (6) changes in the thermal regime of ocean crust, and (7) regional uplift and subsidence. The whole erosion-deposition system is affected by sealevel changes where only the areas above the erosional base are affected by regional uplift and/or subsidence. This model has been used to reconstruct the Rocky Mountain uplift event. Results in the Mississippi River basin - Gulf of Mexico system correspond well with independent estimates of topographic changes.

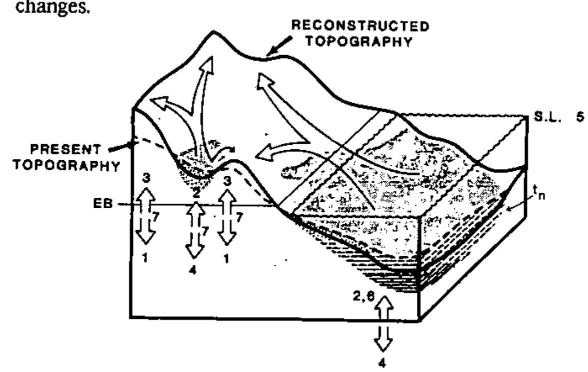

Figure 23. Diagram illustrating the principles of mass-balance modeling in a system of sedimentary sources and sinks. Numbers by arrows correspond to processes discussed in text. For an isochron t_n, sediment in the basin is redistributed about the source area using inverse methods (Hay *et al.*, 1987).

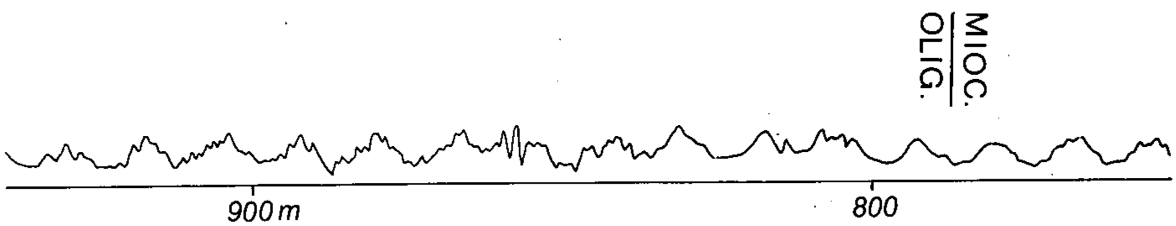

Figure 24. Cyclicity in resistivity log of Oligo-Miocene muds of North Sea. Cycles average 12-13 m, and may represent the 400 ka eccentricity cycle. British Petroleum U.K. 3/29-1. (A. Fischer, *pers. comm.*)

New Opportunities

Much of the paleontological, sedimentological and geochemical work that has been carried on in the past will bear fruit increasingly as the database grows, and as our tools grow sharper. The opportunities here discussed are some that have emerged recently, and that impinge on the planning of ocean drilling operations. There is a need to gather new kinds of data, and to drill new arrays of sites. These opportunities are centered on three main topics : the development of a new high-resolution stratigraphy, the definition of climatic sensitivity in different modes, and the charting of changes in oceanic circulation patterns through geologic time. These studies are vital to oceanography - modeled or not.

To Improve Stratigraphic Resolution

Stratigraphic sequences of varying ages have now yielded the fingerprints of the earth's orbital variations, timed at c. 21, 41, 100, and 400 ka. These occur in various combinations, and when used in conjunction with biomagnetostratigraphy, they endow sensitive facies with built-in chronometers more accurate than any others in use. Such cycles can be discerned in the various borehole and shipboard logs of high resolution (Figs. 3, 24). Adaptation of some of these logging methods to ocean drilling has already revealed such cycles (Fig. 11). The development of such a cyclochronology will be a service to all branches of geology, and is essential to modeling paleoclimatology and paleoceanography where much of the action requires good time resolution. Virtually all the techniques discussed in earlier sections must be applied at high resolutions, requiring greater sampling intensity. The development of such a stratigraphy will also contribute directly to the next topic, that of defining the sensitivity of the climate system.

To Define Climatic Sensitivity in Different Modes

From the perspective of numerical modeling, a strong link has become apparent in recent years which unifies our attempts to understand environmental change in the most recent past and distant past. This is the recognition that pervasive environmental changes have occurred wherever one looks in the sedimentary record in response to changes in the earth's orbit. Climates in the distant past have not been so different from more recent climates in the sense that they retain a certain amount of sensitivity to small-amplitude, high frequency changes in solar radiation reaching the earth (Figs. 2,

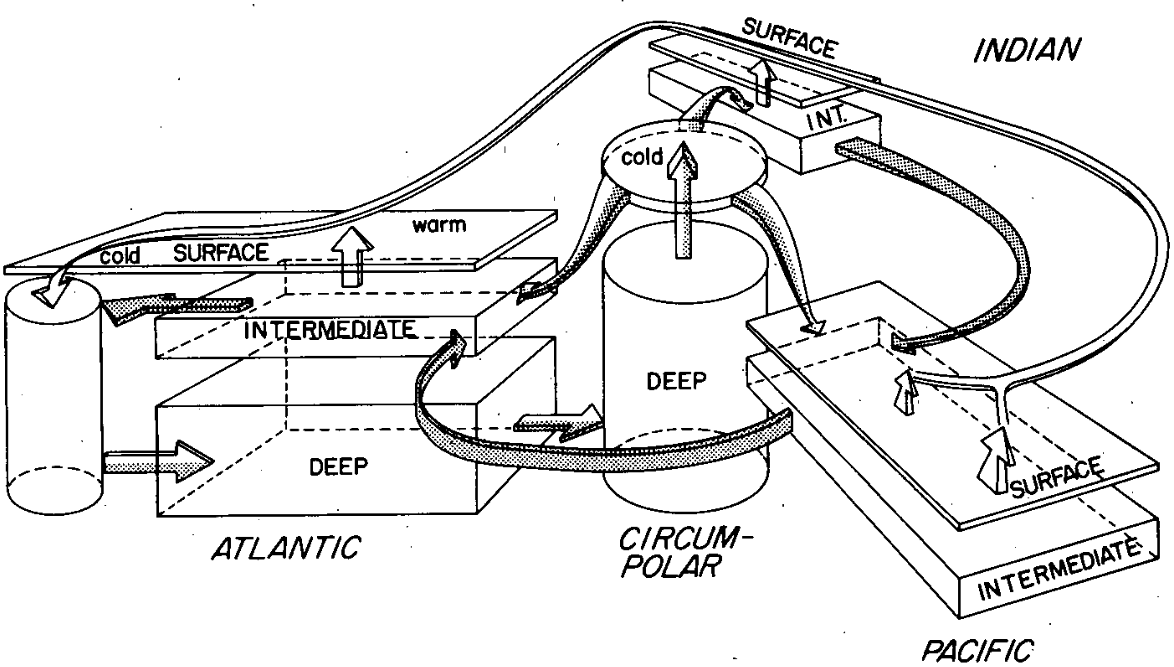

Figure 25. Simplified intermediate-water transport cycle in a model of Holocene thermohaline circulation. The Antarctic Intermediate Water (AAIW) splits, with water in the "warm" pathway (unshaded arrows) upwelling and recirculating into the surface Atlantic via the Indian Ocean. The "cold" intermediate component (stippled arrows) recirculates cyclonically into the Atlantic where it is eventually entrained into the North Atlantic Deep Water source. Because of the meridional transport, regional differences in geochemistry occur. These patterns have changed during the Cenozoic, with global consequences for atmospheric and ocean chemistry. A drilling strategy to investigate these changes must monitor them in each ocean basin along transects that sample a range of paleodepths (R. Keir, in prep.).

3). On the other hand, past climates have left abundant evidence of having switched modes. Past climates have shown variable sensitivity to particular parts of the orbital forcing during different time periods. Even the characteristics of two climates both of which are warm, such as the Eocene and Cretaceous, are distinctly different from each other. We see understanding of the "mode switching" to be a central theme guiding paleoenvironmental research in the future. Great progress can be made in quantitatively understanding past environmental changes if we can reinterpret past observations of long-term trends in the sediment record in light of the mode changes which accompany the trends.

For these reasons, the pursuit of orbital cyclicity in the oceanic stratigraphic record comes to be an item of high priority. While the delineation of the cycles will depend largely on a combination of shipboard and downhole logging, the identification of the sedimentary response to forcing depends on core study. Of particular interest will be studies of transects that will trace cyclic sequences from the top of a rise, where the cycle may have been expressed by carbonate productivity, down the flanks to depths where overprints from dissolution cycles become dominant, or from a carbonate facies into a detrital facies.

To Define Ancient Circulation Patterns

New arrays of HPC/XCB sites should make it possible to extend the existing coverage of data at critical time periods to the global arrays needed to approach the experimental phase of environmental studies. In the case of the Miocene, present control is inadequate in the north and south Pacific, the high latitudes, the tropical Atlantic, and the Indian Ocean. In the Pliocene, major gaps occur out of the range of traditional piston coring. Although the problem of finding Paleogene sequences of suitable quality in HPC/XCB range is difficult, the flanks of rises offer several opportunities. As illustrated in Figure 25, a drilling strategy to monitor changes in the thermocline circulation must aim to provide samples at different water depths and in different ocean basins. A strategy to monitor changes which incorporate interactions of the atmosphere with the oceans, and define the wind-driven ocean circulation, must aim to define tropical and polar temperatures, to characterize atmospheric wind direction through eolian sediments and other indicators, and to focus on the role of the global hydrologic cycle.

Recommendations

Drilling arrays

Arrays of double-cored HPC and XCB holes with appropriate high-resolution logging will be needed to learn in detail how the ocean and atmosphere respond to orbital and tectonic forcing. Among the best places to study these responses are across environmental gradients associated with major currents and fronts, and across bathymetric gradients along the flanks of ridges and rises. Specific drilling recommendations are given in the last section.

Cycle Reconnaissance

While orbital cyclicity has emerged from numerous studies of outcrops, cores and well-logs, we know as yet very little about the distribution of the individual cycles (precession, obliquity, eccentricity) in terms of latitude, facies, and age. A reconnaissance is needed, which must integrate sample studies, downhole, and shipboard logs. Downhole logging will be especially useful in deep holes which will not be double-cored and may be discontinuous.

Logging

We recommend (1) making high-resolution, downhole logging a standard feature of the ocean drilling program; (2)

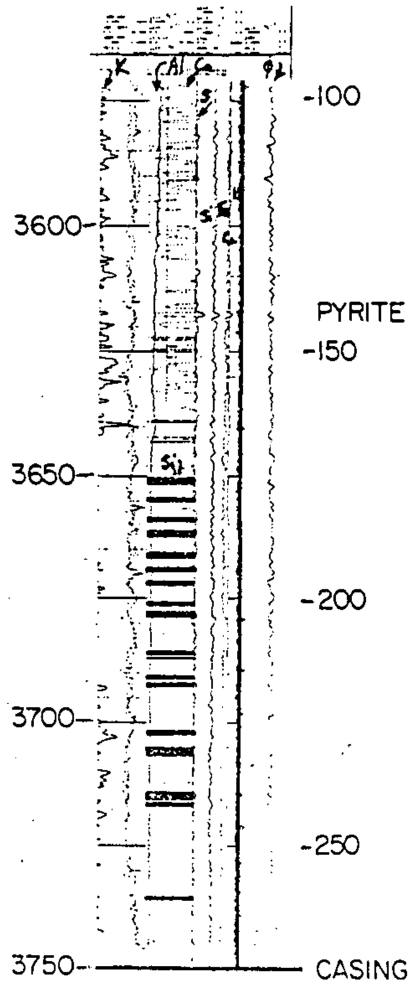

Figure 26. Neutron activation log of sedimentary section of hole 504B, ODP Leg 111, done through casing. Chert stringers indicated by abundant silicon zones (black bars). Clay-rich zone shown by high potassium 3570 to 3642 m. From Lamont-Doherty Borehole Research Group (1987).

more extensive use of high-resolution, onboard logging of cores (especially magnetic susceptibility logs); (3) increased efforts to calibrate both types of logs against normal laboratory analyses; (4) that logging tools and hole conditioning be optimized to decrease the time required for logging; and (5) continued experimentation with techniques that can log through drillpipe and casing (Fig. 26).

Arctic and Continental Margin Drilling

Arctic and continental margin drilling offer important opportunities that are discussed below.

SEALEVEL CHANGES

Scientific Goals

A first-order goal of scientific drilling should be to improve our knowledge of the history of global sealevel changes. We urgently need reliable, quantitative information, particularly on the amplitude and timing of major oscillations in global sealevel. The scientific importance of such information is difficult to overestimate. Models of global sealevel have implications for nearly every branch of geology, geochemistry, geophysics, and evolutionary biology. For example, information on sealevel is central to our understanding of stratigraphy, because the sediment-producing machine of erosion, transport, and accumulation is a system driven strongly in every region by fluctuations in relative sealevel. These local fluctuations, in turn, are caused by interactions between global sealevel and local tectonic and sedimentary processes. Once the global component of the relative change is known, it becomes possible to sort out and quantitatively model the local influences of thermotectonic subsidence, lithospheric flexure, sedimentation, and compaction. Furthermore, accurate knowledge of the amplitude and frequency of major oscillations in global sealevel will lead not only to a deeper understanding of the global tectonic processes which cause changes in the volume of the ocean basins, but also to a better knowledge of the climatic processes which change the volume of ocean water by glacial entrapment or by the desiccation of isolated basins. Finally, it is important to have an accurate model of eustatic history because changes in sealevel have a significant influence on the physical properties of the atmosphere and on the physical, chemical, and biological properties of the ocean.

The Experimental Challenge

How can this goal be achieved ? Given some permanent dipstick that remains fixed with respect to the center of the earth, and some sedimentary or chemical record calibrated to this dipstick, the observational problem of determining the eustatic sealevel curve would be relatively simple. Unfortunately, no such dipstick has been discovered. All stratigraphic records, whether on the continents, continental margins, or sea floor, shift their vertical position with time, and therefore reflect local changes in relative sealevel ; and the best available isotopic indicator ($\delta^{18}O$) measures not sealevel, but a combination of ice-volume, ice-composition, water temperature, and other influences.

What therefore might appear at first glance to be nothing more than a demanding observational problem - solvable in principle by an appropriately organized program of surface sampling, seismic profiling, and exploratory drilling - turns out in fact to be a challenging *experimental* problem, a problem that will be solved only if the observational effort is closely tied to quantitative *geophysical modeling* of subsidence and compaction, and to *geochemical modeling* of the non-ice-volume components of $\delta^{18}O$.

The Opportunity

As described below, substantial progress has been made since COSOD I on both the observational and modeling sides of the sealevel problem. These advances make it possible for us to build a scientific strategy around three independent approaches. Each approach has its limitations and advantages. The atoll approach, based on recent developments in the stable-isotopic correlation of carbonate sequences, uses the stratigraphic record of atoll carbonates as dipsticks in regions having a subsidence history that is simple enough to be predicted with useful accuracy. Although this strategy yields discontinuous records with variable resolution, it appears to offer the best chance of obtaining reliable, quantitative, low-frequency (<2 Ma) information on the amplitude of Tertiary eustatic sealevel variations. The passive margin approach, developed by Vail and his colleagues, derives an estimate of global sealevel from stratigraphic information coded as a coastal onlap and offlap pattern on different continental margins. Along any particular margin, relative sealevel depends on whether the basin is subsiding faster or slower than global sealevel is rising or falling. Because the uncertainty of our prediction of the subsidence in these areas is of the same order as the sealevel oscillations we are attempting to observe, the Vail procedure necessarily involves the stacking of information from different margins, and the assumption that any general trends observed are eustatic. Although this strategy provides information on relative sealevels for the entire Phanerozoic - with a resolution during the Tertiary on the order of 2 Ma - major uncertainties remain about its validity as a procedure for determining global sealevel (Watts, 1982 ; Watts and Thorne, 1984 ; Summerhayes, 1986). The isotopic approach infers changes in global ice volume from the isotopic composition of oceanic microfossils. Although this strategy can provide continuous information at periods as short as 10 ka, its reliability depends strongly upon the accuracy of assumptions about water temperature and the isotopic composition of glacial ice (Miller *et al.*, 1987).

Each of these approaches involves certain assumptions and has stratigraphic limitations with respect to range and resolution. But because the assumptions and limitations differ among the three approaches, it should in principle be possible to constrain our knowledge of eustatic changes by comparing sealevel estimates derived by the three methods for the same stratigraphic interval. Once this objective is achieved, it should then be possible to interpret apparent discrepancies among the estimates in ways that will significantly advance other aspects of our knowledge of earth history. For example, initial comparisons of the three methods over the interval 0-20 Ma suggest that the passive margin approach leads to estimates of sealevel that are too high between 3 Ma and 17 Ma. If this discrepancy should be confirmed by the results of the research program recommended in this document, it would then be possible to extract the eustatic component from onlap curves developed for individual continental margins - and so provide a test for models of local tectonic and compaction histories. Similarly, a comparison of isotopic data and sealevel inferences from atoll drilling would yield more information about climatic and sealevel history than would be possible by examining each record by itself. If, for example, isotopic and paleontologic studies indicate that a change in the isotopic composition of a given set of forams reflects primarily a change in water composition, then it might be possible to calculate both the volume and composition of glacial ice.

Progress since COSOD I

The Continental Margin Approach

Aware of the importance of sealevel changes, and stimulated by the publication in 1977 of coastal onlap curves interpreted in terms of relative sealevel by Peter Vail and his colleagues at Exxon Production Research (Vail *et al.*, 1977), the authors of the COSOD I report gave high priority to investigations of sealevel history. Their emphasis was on the asymmetrical oscillations of the coastal onlap curve published in 1977, and on the influence these fluctuations in relative sealevel have on the distribution and nature of marine sediments. Later publications made interpretations in terms of eustatic changes (Vail and Hardenbol, 1979 ; Haq *et al.*, 1987).

Since COSOD I, Vail's sequence boundary hypothesis has become a major topic of research on continental margins and sealevel. Seismic stratigraphic methods, published a decade ago, have become benchmarks with widespread application by researchers in both academia and the petroleum industry. Many aspects of the methods, particularly those associated with environmental interpretation and facies analysis, are in broad use. Quite apart from the question of their applicability to the eustatic problem, these methods and Vail's model have led to major advances in our knowledge of earth history. The methodology for interpreting coastal onlap curves in terms of eustatic changes is a few years younger, having been published two years before COSOD I (Vail and Hardenbol, 1979). These methods have since been refined (Haq *et al.*, 1987), resulting in significant revisions of this model of Tertiary sealevel history (Fig. 27).

One of the most successful attempts to reconstruct relative sealevel changes on passive continental margins was

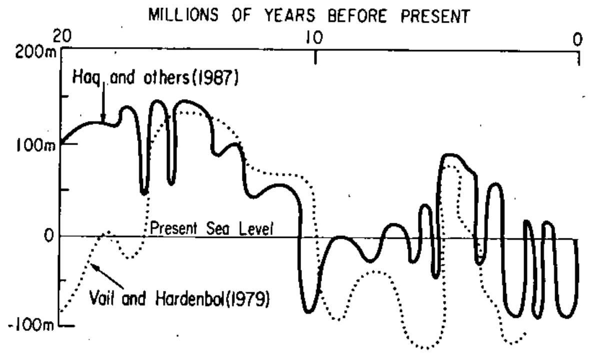

Figure 27. Eustatic sealevel estimates derived from coastal onlap curves by Vail and Hardenbol (1979) and Haq *et al.* (1987) for the past 20 Ma. Note that the earlier estimates are substantially below the later estimates for significant portions of the interval studied (Halley and Ludwig, 1987).

drilling by DSDP Legs 80, 93, and 95 (Van Hinte *et al.*, 1987). These transects of the Irish (Goban Spur) and New Jersey continental margins demonstrated that chronostratigraphic and seismic stratigraphic evidence for sealevel falls compares well with the Vail paradigm in some intervals, but requires further documentation in many intervals. For example, upper slope and shelf sections, the most sensitive to sealevel changes, were not drilled, while large stratigraphic gaps remain (*e.g.* the lower-middle Miocene was very poorly represented). Despite limitations, these legs demonstrated that transects of passive margin are among the most powerful strategies for unraveling the record of relative sealevel changes on passive margins.

The Isotopic Approach

It is now widely recognized that Cenozoic records of oceanic $\delta^{18}O$ contain valuable information about temperature and ice-volume history. From the sealevel perspective of this chapter, the main problem is to remove the effect of temperature. For the late Pleistocene, where ice-volume changes dominate the $\delta^{18}O$ record, the problem is more easily constrained (Shackleton and Opdyke, 1973). In mid-ocean tropical sites, where temperature changes are small, the planktic record provides useful information on ice volume change. Benthic records are now known to contain a small but significant component reflecting deep water temperature change (Labeyrie *et al.*, 1987 ; Shackleton, 1987). Clearly, the problem of separating ice-volume and temperature effects is more difficult in the Tertiary, where we seek information on ice volume in the face of uncertainties about the geographic location and isotopic composition of glacial ice, about the temperature of surface and bottom waters, and about diagenetic effects in samples that have been buried deeper than a few hundred meters.

At the time of COSOD I, it was generally assumed that the earth was essentially ice-free prior to the middle Miocene. But Matthews and Poore (1980) argued that substantial continental ice sheets were in existence at least since the earliest Oligocene. This view has been supported by later studies (Miller and Fairbanks, 1985 ; Keigwin and Keller, 1984 ; Miller *et al.*, 1987). Since COSOD I, the challenge of determining thermal and ice-volume history has been met by the acquisition and paired analysis of closely spaced samples of benthic and planktonic forams in a large number of HPC cores covering the last 35 million years in the Pacific and 70 million years in the Atlantic ocean basins. The present status of our knowledge is summarized by Miller *et al.* (1987), who inferred ice-growth events at c. 35, 31, 25, 15-13, and 10 Ma. These are observed as intervals of high $\delta^{18}O$ in benthic foraminifera (Fig. 28) associated with increases in planktonic $\delta^{18}O$ values. Other growth events occurred at c. 5 Ma (Keigwin *et al.*, 1986) and 2.4 Ma (Shackleton *et al.*, 1984).

In order to use the isotope record as a proxy for glacioeustatic sealevel, the relationships between seawater $\delta^{18}O$ and ice volume (hence sealevel) must be established. This can be done in two ways: (1) by modeling the development of ice caps versus $\delta^{18}O$ composition, emphasizing the early stages; and (2) by empirically determining a relationship between independent sealevel estimates and $\delta^{18}O$ changes. The first approach involves combining an ice-sheet model (*e.g.* Oerlemans' model discussed above) with an atmospheric circulation model that calculates and tracks the $\delta^{18}O$ changes. The latter approach has been implemented for the Quaternary by comparing sealevel history obtained from atoll subsidence with the $\delta^{18}O$ record (Fairbanks and Matthews, 1978). A major goal of atoll drilling and paleoenvironmental transects is to establish such an empirical calibration for the Tertiary.

Improvements in Dating Carbonates

Strontium isotope correlation of Tertiary carbonates allows time resolution in shallow-water limestones that is comparable with microfossil dating of deep-sea deposits. Changes in the value of $^{87}Sr/^{86}Sr$ in seawater during the Tertiary have been well-documented (DePaolo, 1986 ; Elderfield, 1986 ; Hess *et al.*, 1986). Carbonate minerals precipitated from open seawater retain an Sr isotope ratio indicative of their time of precipitation. The ability to resolve time using strontium isotopes depends on how rapidly the ratio was changing during the time of interest. For much of the Tertiary the resolution of time using strontium ratios varies between about 300 000 and 3 000 000 years.

Installation of a modern cryogenic magnetometer on the *JOIDES Resolution* has enhanced the capability of measuring weakly magnetized rocks such as atoll limestones.

Development of an Atoll Drilling Strategy

Sr isotope dates from complete cores through atolls (Ludwig *et al.*, in prep.), combined with magnetostratigraphy and conventional paleontology, provide the best records of subsidence rates for cooling oceanic crust. Such cores also provide evidence for subdividing carbonate caps into discrete strata, each stratum being separated by subaerial disconformities, and each being deposited during a brief interval of atoll flooding during a sealevel rise (Halley and Ludwig, 1987). The thickness of each stratum is a minimum estimate of the rise in sealevel. An estimate of atoll subsidence during periods of exposure may be calculated from the time represented by a subaerial disconformity (the difference in age of limestones above and below the disconformity) multiplied by the rate of atoll subsidence. This amount of subsidence is also a minimum measure of the amount of sealevel drop during exposure. If sealevel had been above the level of the subsiding atoll, a new episode of limestone deposition would have recorded atoll flooding during the period represented by the disconformity. By calculating estimates of sealevel rises from the thicknesses of atoll strata, and estimates of sealevel drops from disconformities, a quantitative although discontinuous sealevel record is produced that may be compared with those derived from other methods (Figs. 29 and 30).

Improvement in Geophysical Models

Subsidence models of the ocean floor and passive continental margins have become increasingly sophisticated since COSOD I. For the ocean floor, the concept of the oceanic lithosphere as a cooling boundary layer on top of a viscous upper mantle accounts for the increase of depth with age. On crust between 0 and 80 Ma the ocean floor subsides with the square root of age. On older ocean floors, the depths in general flatten with spatially correlative swells and valleys.

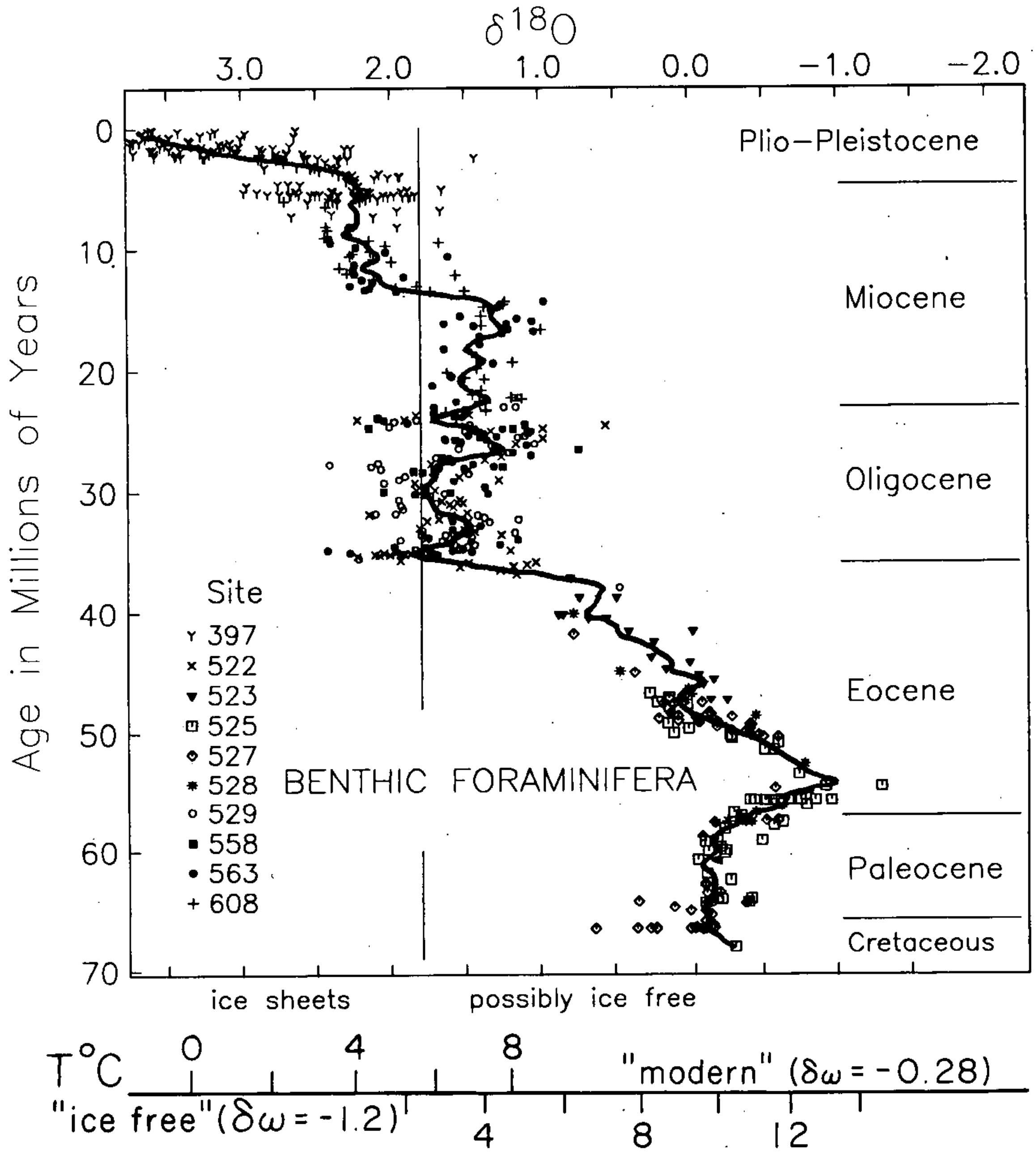

Figure 28. Composite benthic foraminiferal oxygen isotope record for Atlantic DSDP sites. The smooth curve is obtained by linearly interpolating between data at 0.1 Ma intervals and smoothing with a 27-point Gaussian filter, which removes frequencies higher than 1.35/Ma. The vertical line is drawn through 1.8 °/•• ; values greater than this suggest the existence of large ice sheets. The temperature scale is computed from the paleotemperature equation ; the lower scale assumes no significant ice sheets ; the upper scale assumes ice volume equivalent to modern values (Miller *et al.*, 1987).

As shown in Figure 31, the flattening in the depths indicates that the thermal boundary layer has reached equilibrium conditions under the older ocean floor (Sclater and Wixon, 1986 and Renkin and Sclater, in press). In addition, the correlation of the swells and valleys with geoid height presents evidence for organized convection in the upper mantle beneath the older lithosphere in both the Western North Atlantic and North Pacific. In most areas that have not been affected by these swells or have been affected by a known amount in the past, it is possible to determine the relative subsidence through time with substantial precision. Examples of well-behaved (predictable) island chains are the Hawaiian chain and atolls to Midway, the Society Islands, the Marshall-Gilbert Islands, and the Duke of Gloucester Islands.

Passive continental margins have been created by the extension of continental crust. If the age of extension and the amount of crustal thinning or extension are known, then it is possible to construct the past subsidence history of the margin through time. The problem with determining a precise subsidence curve on the continental margins is that this subsidence is substantially affected by both the loading effect of the sediments on the margin and compaction. Though it is known that the old margins behave elastically, there is no general consensus for exactly how the load should be treated. In addition, the compaction of sediments as the sediment dewaters on burial needs to be accounted for. Though we have a general idea of how this compaction occurs, it adds another complication to determining the subsidence history. As a

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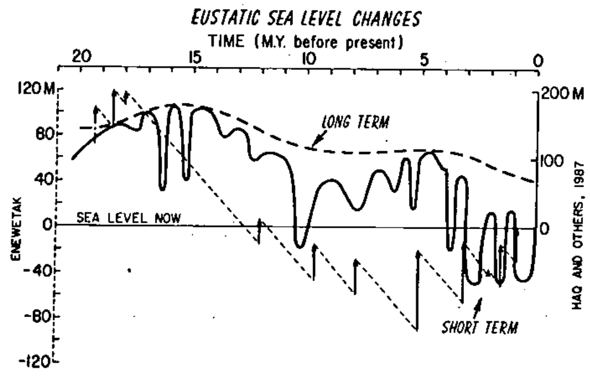

Figure 29. Comparison of atoll (Enewetak) sealevel history, dashed line, with the eustatic sealevel curve of Haq *et al.* (1987), solid line. The length of each arrow represents the thickness of a limestone unit that was deposited when the atoll was flooded during a sealevel rise. Sr-isotope dating indicates that these units were deposited quickly relative to atoll subsidence rates. The units reflect an estimate of sealevel because these shallow water carbonates accumulate at rates that keep pace with sealevel rise. The arrows (limestone units) are placed relative to one another along dashed lines that represent the rate of atoll subsidence. The distance between arrows is the time of the subaerial disconformity separating limestone units. Subaerial disconformities also occur within limestone units but are of too short duration to be resolved by Sr-isotope dating. These disconformities represent higher frequency sealevel fluctuations that are "filtered" by the limitations of the dating technique (Halley and Ludwig, 1987).

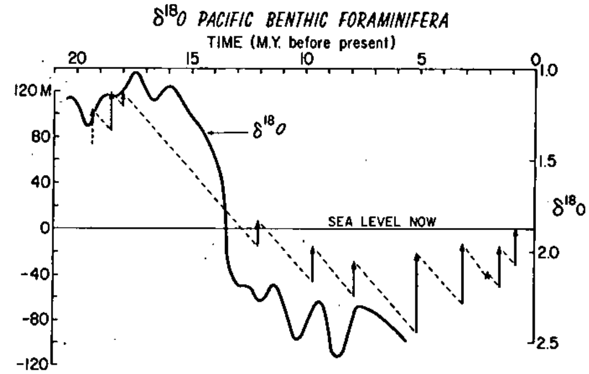

Figure 30. Comparison of the Enewetak sealevel history with variation of $\delta^{18}O$ in Pacific ocean benthic foraminifera (after Miller *et al.*, 1987). $\delta^{18}O$ of benthic foraminifera is a function of deep-sea temperature and salinity as well as the amount and isotopic composition of glacial ice. Nevertheless, simultaneous consideration of the conspicuous low frequency signal (<2/Ma) evident in seismic-stratigraphically generated sealevel curves, $\delta^{18}O$ curves, and the Enewetak sealevel curve suggests that ice-volume fluctuations produce the dominant signal in all records (unpublished figure from Halley and Ludwig, 1987).

consequence of these two additional assumptions in the subsidence calculations, it is in general more difficult to predict subsidence on the margins than on a well-understood portion of the ocean floor (Van Hinte, 1978 ; Watts and Steckler, 1979 ; Watts *et al.*, 1982 ; Watts and Thorne, 1984). This is also true even if the ocean floor has been perturbed by a thermal plume from the upper mantle.

The Antarctic Experiment

From the advent of early ocean coring programs, the geological record of glaciation on Antarctica has been of major interest to students of sealevel and climate. As reviewed above, recent studies on Leg 113 suggest that glacial development probably began during the late Paleogene in East Antarctica, and once ice-covered, did not undergo significant deglaciation. The same data suggest that the West Antarctic Ice Sheet may have originated in the late Miocene. Now the time has come to evaluate both the indirect sedimentary and isotopic evidence from ODP and the direct field evidence from Antarctica (Denton *et al.*, 1986) in the light of the results of modeling studies which investigate the behavior of the Antarctic Ice Sheet (Oerlemans, 1982) and the global atmosphere (Barron and Washington, 1984) under different thermal regimes.

Drilling Strategy

As argued above, an important opportunity exists to advance our knowledge of the history of eustatic sealevel by drilling sites specifically chosen to address the problem. These sites can be considered to comprise three different sampling arrays : (1) an atoll array, consisting of sites in both living and drowned atolls ; (2) a passive margin array, consisting of transects chosen from continental margins having different subsidence histories ; (3) HPC/XCB drill sites chosen to fill in, extend, or strengthen the isotopic record. The last-named array is identical to the environmental array discussed earlier in this chapter.

Atoll Drilling

In carrying out the atoll drilling strategy it is important to locate the sites in areas where the uncertainties in modeling subsidence history are minimal. We have good reason to believe that these conditions are met in the Marshall-Gilbert Islands. The ocean floor in this area has a small geoid anomaly and low heat flow (Renkin and Sclater, in press). Thus, it appears that these islands lie on crust that is locally compensated ; and it is probable that they have had a very straightforward subsidence pattern since the Eocene, when they where all at sea-level. If it can be demonstrated unequivocally that this subsidence extends throughout all the islands, then it is most likely due to thermal cooling. As we know the overall pattern in the Eocene, and the present depth of the basement, then the subsidence can be modeled to a few tens of meters with some degree of certainty.

Alternative areas suggested for these studies are Markus/Necker Rise and the Line Island chain. Unfortunately, both of these areas have substantial positive geoid/depth

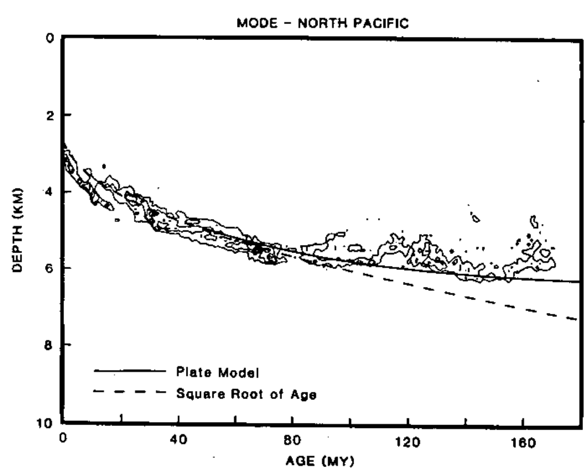

Figure 31. A plot of the depth of the ocean floor, presented as contours about the mode, against age for all data in the North Pacific (after Renkin and Sclater, in press).

relations similar to that over Midway, indicating post-Neogene reheating and possible uplift. Because the subsidence histories of these islands are unknown at the present time, these islands are unsuitable for a sealevel study without much more extensive drilling and surveying than would be necessary for the Marshall-Gilbert chain.

The most rapid subsidence of oceanic islands occurs following the cessation of volcanism and the onset of crustal cooling. The most continuous record of atoll subsidence (highest sedimentation rate) develops immediately after the volcanic edifice subsides below sealevel and during the periods of rapid crustal cooling. Atoll drilling can be targeted toward those atolls that would be expected to have the best (most continuous) record of the time periods of interest. For example, Enewetak is one of the oldest atolls in the Marshall Island chain and has Eocene limestones overlying basalts. If the major sealevel fall at 28 to 31 Ma is targeted, the best record may lie beneath an atoll in the southern Marshall Island chain on an atoll about 20 million years younger than Enewetak. Similarly, younger sealevel events could be targeted beneath atolls of the Hawaiian chain, the Society Islands and other, tectonically simple island groups. Each targeted atoll would be the centerpiece of a transect of drill sites along an island chain with sites chosen to test the validity of the assumption of a relatively simple subsidence history for atolls or seamounts along the chain. In all, transects are needed across three living or drowned atolls.

Passive Margin Drilling

We consider that it would be prudent to focus the continental margin array on three intervals of time in which coastal onlap curves have suggested major sealevel events: mid-Miocene, mid-Oligocene, and early Eocene. These times are chosen for the following reasons. (1) In the mid-Miocene there is a major shift in the oxygen isotope records of benthic and low-latitude planktic forams, suggesting a major change in ice volume (hence also sealevel), at about 14 Ma (Miller *et al.*, 1987). In contrast, only minor fluctuations have been inferred by Haq *et al.* (1987). (2) In the mid-Oligocene, the oxygen isotope signal suggests that there were substantial ice caps, but it does not vary as much as it does during earlier and later events, suggesting less ice growth (Miller *et al.*, 1987). In contrast this period contains the largest inferred sealevel fall of the entire Phanerozoic, at 30 Ma (Haq *et al.*, 1987). (3) In the early Eocene, isotopic data suggest the warmest climate of the Tertiary and possibly an ice-free world (Miller *et al.*, 1987). Sealevel was also apparently very high, with many small fluctuations, but shows a surprisingly substantial fall during this time (at 49.5 Ma) (Haq *et al.*, 1987). Clearly these apparent discrepancies between different data sets are in need of resolution.

Miller *et al.* (1987) consider that the evidence from isotopic data and from the record of erosion on continental margins suggests that the mechanisms and rates of sealevel change differed between the late and early Tertiary, with glacioeustatic changes restricted to the past 36 Ma, and earlier erosion being controlled by global changes in the rate of sea floor spreading. This concept merits thorough investigation.

Careful inspection of the Vail approach to deriving global sealevel records suggests that while several of the unconformities caused by falls in sealevel may indeed have been global, many - especially third-order ones - are not necessarily global (*e.g.* see Miller *et al.*, 1987; Christie-Blick *et al.*, 1987; Hubbard, 1987). In any case, their duration is at the limit of biostratigraphic resolution in Paleogene and older rocks, so it will be difficult to prove or disprove that they are indeed global. Moreover, the very method of calculating the timing and amplitude of the supposed sealevel oscillations has been called into question recently (*e.g.* Miall, 1986; Summerhayes, 1986; Christie-Blick *et al.*, 1987). At the COSOD II meeting Haq described the sealevel curve as essentially a hypothesis based mostly on data from Europe and North America, with the amplitudes of sealevel change derived by subjective evaluation of different input curves.

Tests of the sealevel curve hypothesis should be made on passive margins with different tectonic histories (*e.g.*, some with drift onset greater than 100 Ma, and others with drift onset less than 70 Ma), for comparison. Margins with relatively simple subsidence histories are required, preferably where there are good outcrop sections on the nearby land, and available oil company data from wells on the continental shelf. At least one transect per margin is needed. It should extend from the continental shelf onto the adjacent abyssal plain so as to be able to detect the sediment displaced from the margin during times of erosion caused by sealevel falls. A near-complete Neogene-Paleogene sequence is desirable, as are the reasonably high sedimentation rates needed to provide high resolution of sealevel signals. Transects should not include fan or delta lobes, whose occurrence may be confused with sealevel signals. As the North Atlantic (1) has been reasonably well-studied (*e.g.* by DSDP on the New Jersey transect), and (2) lies within the main database area that supports the Haq *et al.* curve, drilling should ideally be concentrated on at least three other passive margins meeting the above criteria, for example in Australasia, in the Indian Ocean, and in eastern Tethys.

Studies should be multidisciplinary, combining biostratigraphy, seismic stratigraphy, magnetic stratigraphy, isotope stratigraphy, well-log analysis, and subsidence modeling, and major survey work is needed to document suitable transects.

Tests confined to seismic stratigraphic profiling and drilling across continental margins will not be enough, in themselves, to crack the problems involved: determining the timing and amplitude of sealevel changes through time. Only by combining different sensing systems (*i.e.* by stacking the records from isotopic data, atoll drilling, and margin drilling) can we hope to pin down the variables within the sealevel system. Each of these sensing systems has its own limitations, not least of which, in the case of seismic stratigraphic interpretation, is the role of subsidence in creating unconformities on continental margins. The idea that unconformities are linked to subtle changes in spreading rate (which could be local or global) may have been dismissed too lightly in the past. The isotope curve holds the virtue that unlike the sealevel record on continental margins it is unaffected by changes in basin shape. Atoll drilling can show us how high sealevel may have been (with range bars), but may not be useful to us much before Eocene times. We need to be aware of these various limitations.

EXPLORATORY DRILLING

Its Continuing Importance

The past 20 years of ocean drilling represent an era of scientific exploration and discovery that have few parallels in the earth sciences. The new knowledge gained - about the structure of the ocean basins, the nature and distribution of ocean sediments, and especially about the history of global climate - is the factual basis for an experimental program designed to understand the causes and mechanisms of global environmental change. As we enter this new phase of ocean drilling, it is important to remember that beyond the frontiers of our knowledge large areas of ignorance remain. Several geographic regions and many parts of the stratigraphic column await exploration. Even in areas with prior reconnaissance, experience demonstrates that every hole yields a surprise and suggests that serendipity will continue to play a significant role in shaping the development of our science. Clearly, any drilling program planned as part of an experimental effort to understand what happened in earth history should go hand in hand with an exploratory program designed to find out what actually did happen in areas and times where we lack information.

Major Opportunities

Arctic Ocean

Polar regions are key parts of the global climate system, strongly influencing terrestrial climate and controlling the formation of deep and bottom waters. In contrast to the Antarctic, which has been studied on several DSDP/ODP legs, the Arctic Ocean is nearly unknown. Northern hemisphere ice cover is only well documented for the past 2.6 Ma, based on subpolar drillsites. Thus, our lack of information on the Cenozoic history of the Arctic Ocean - particularly with regard to changes in sea-ice cover, temperature, salinity, density structure, and productivity - is a major gap in our ability to understand and model global environmental change.

The central Arctic Ocean basin is the place to study : (1) the paleoceanography and climate in preglacial Late Cretaceous and Paleogene times, when the existence of temperate, biologically productive surface waters (and probably oxygen-deficient bottom waters) has been inferred from fragmentary sediment cores on the Alpha Ridge (Kitchell and Clark, 1982) ; (2) the initiation and earliest history of northern hemisphere glaciation ; and (3) the climatic evolution since the upper Miocene, and particularly the long-term variability of ice cover (see Blasco *et al.*, 1987).

The fringes of the Arctic Ocean basin, especially the Bering Sea and the Norwegian-Greenland Sea, are the places to study the time of initiation of the present pattern of deep-water formation, the variations in this pattern with time, and the linkages between these variations and oceanic changes elsewhere in the world ocean.

JOIDES Resolution can be used for drilling around the margins of the Arctic basin. Elsewhere, new platforms and different technologies are required. According to Blasco *et al.* (1987), options include : (1) Passively drifting ice islands (suitable for multi-year use) or artificially reinforced ice platforms (suitable for one season). (2) Drill ship or ice-strengthened semi-submersible, frozen into the ice ; here there is no possibility for moving the platform without substantial additional ice breaker support. (3) Ice breaker with drilling capability (such as the Canadian Class 8 ice breaker which is to be constructed in the near future) ; the advantage here is the possibility of moving to pre-selected drilling locations.

Continental Margins

Continental margins offer several unique opportunities to investigate the processes of climatic change : (1) currents and energy gradients are strong in this region, which simplifies the task of documenting them from the geologic record ; (2) boundary currents are sensitive indicators of global energy gradients ; (3) productivity is high and cyclical changes in productivity have large amplitudes in this region ; (4) sediments accumulate rapidly, yielding opportunities for good time resolution and the detection of Milankovitch cycles ; (5) the relationship between changes in the ocean system and the evolution of land climates can best be studied where land climate leaves a detectable imprint on the marine record, as it does along the continental margins through the deposition of pollen, phytoliths, clay minerals and other terrigenous material ; and (6) stratification of water masses can be studied along depth transects. This is an important advantage, not only for studies of Cenozoic oceanography, but also for investigating the causes of anoxic conditions that led to the formation of Cretaceous black shales.

Although drilling along continental margins offers important opportunities for studying environmental change, it is well to remember that these areas also present difficulties. The high deposition rates that make these areas so desirable for coring may also place stratigraphic targets beyond the range of HPC drilling. In addition, sequences with undisturbed, continuous, autochthonous sedimentation may be difficult to find. Clearly, it is particularly important in these areas to conduct extensive pre-site surveys. Where investigations having paleoclimatic objectives can be combined with the sealevel transects discussed above, both programs would benefit.

Older Sediments

The oldest parts of the ocean floor reach back to a very different world of the Jurassic, when there was one continental mass (Pangea) and the largest part of the world was covered by a gigantic super-Pacific (Panthalassa). This time also preceded the late Jurassic rise of calcareous plankton, which redirected the bulk of carbonate sedimentation from the shelves to the deep sea. These conditions therefore offer special opportunities to understand how the oceans and atmosphere operate under boundary conditions very different from those of later times. In turn, this knowledge will provide a solid foundation for understanding how ocean circulation patterns evolved during the Cretaceous and later phases of continental fragmentation.

Unfortunately, subduction has destroyed most of the Jurassic oceanic record, and what is left is deeply buried. The Jurassic is therefore a difficult target, especially if the sediments overlie an oceanic crust. The position of the top of the Jurassic varies between 5000 m and 6300 m below sealevel, and up to 1600 m subbottom. Lesser water depths and lesser penetrations are required in those areas where the Jurassic strata overlie a continental crust, as is the case for the Galicia margin (Site 639), the Moroccan margin (Sites 544-547) and the Falkland Plateau (Site 330). In all, 17 sites have so far yielded Jurassic sediment, but the sampling is uneven : nearly all are in the North Atlantic, which at that time was part of the tropical Tethys. The only other sites are from the Falkland basin and one from the Indian Ocean. We have nothing from the then-gigantic Pacific, which is thought to retain the largest areas of Jurassic crust.

Although the Jurassic record that is available for drilling will hardly suffice to provide a comprehensive record of oceanography, it may still yield important clues to a number of questions ; the Cretaceous record is considerably better than the Jurassic. Major problems for both the Jurassic and Cretaceous focus on global warmth, widespread anoxia, high global sealevels, carbonate chemistry, and the evolution of atmospheric and oceanic circulation during the early phases of the breakup of Pangea.

We therefore recommend that further efforts be made to reach basement in the oldest parts of the Pacific, and that our library of Jurassic and Cretaceous samples be expanded. Many of the gaps, particularly for the black shale problem, require continental margin transects which define the vertical structure of anoxia and its relationship to regions of high productivity and to the structure of the ocean circulation.

RECOMMENDATIONS

General Drilling Requirements and Priorities

As discussed above and summarized in Table 1, we require :

(1) A paleoclimate array consisting of logged, double-cored HPC/XCB sites supplemented by rapid, high-resolution downhole and shipboard logging in each ocean basin to define changes in oceanic features such as fronts, upwelling zones, SST gradients and changes of properties with paleodepth, in detail back through the Neogene and with broader coverage through the Paleogene. (Priority One)

(2) Transects drilled across living and drowned atolls in a region such as the Gilbert-Marshall Islands where subsidence history is simple, with the object of constraining the Cenozoic eustatic sealevel curve. Ideally, three transects should be obtained. (Priority One)

(3) Shelf-to-basin transects across passive margins, coordinated with seismic profiling and land drilling, with the aim of defining the Cenozoic sealevel histories on margins with different tectonic histories. Ideally, three such transects should be obtained, at least two of which should be on margins well away from the North Atlantic. (Priority One)

(4) Exploratory drilling in the Arctic Ocean to discover the history of this key climatic sector. (Priority One)

(5) Exploratory drilling along continental margins to fill in gaps in our knowledge of oceanic and continental history in these climatically sensitive and economically important areas. (Priority Two)

(6) Exploratory drilling in Cretaceous and Jurassic sediments to expand our knowledge of early ocean history. (Priority Two)

As discussed earlier in this chapter, we recommend that :

(1) Rapid, high-resolution downhole and shipboard logging should be a standard feature of the environmental drilling program.

(2) Every HPC and XCB site should be double-cored.

Specific Drilling Recommendations and Estimates

The estimates of drilling time required to achieve the program described above have been derived mainly from the data compiled recently by the ODP Engineering Group (OPD Technical Note N° 1, December 1986).

The estimates of time required for various coring/drilling configurations (HPC, XCB, RCB, re-entry) as well as for logging are considered very accurate in well-known environments such as those considered for most paleoclimate transects. For other targets we have used time estimates based on previous experience with the Deep Sea Drilling Project's ship *Glomar Challenger* and they should be used with caution for planning purposes.

Paleoclimate Array (Priority One)

Neogene HPC/XCB Array: Understanding the Ocean System. The objectives here are *high resolution* and *global coverage*, to be achieved by a global array of HPC sites taking advantage of the latitudinal distribution of aseismic ridges and plateaus in the major ocean.

The experience from DSDP and most recent legs of ODP clearly demonstrates that HPC/XCB coring with high resolution and full recovery is feasible through the entire Neogene section in many areas (see for example Legs 85 and 90 of DSDP and Leg 115 of ODP).

Ideally, we should obtain *20 transects* (of four to six sites each) covering a wide range of latitudes and water depths. Each transect will represent approximately *20 to 25 days* of drilling and logging operations :

* Pacific Ocean = *8 transects* (for example : Sounders Ridge, Hess Rise, Shatsky Rise, Magellan Rise, Manihiki Plateau, Chatham Rise, Lord Howe Rise ; and sections on seamounts).
* Indian Ocean = *6 transects* (for example : Maldives, Ninetyeast Ridge, Seychelles Bank, Madagascar Ridge, Broken Ridge, Gaussberg Ridge).
* Atlantic Ocean = *6 transects* (for example : Norwegian margin, Ceara Rise, Demarara Rise, Sierra Leone Rise, Rio Grande Rise, South Georgia Rise).

The grand total for this ideal global array comes to a minimum of 400 to 500 operating days (on site). A full year of drilling would significantly improve our knowledge of the Neogene ocean.

Paleogene HPC/XCB Array: Deciphering the Onset of Modern Ocean Circulation. The objectives here are to obtain a global array of sites and paleodepth transects which sample both planktic and benthic records. In most cases, Paleogene sediments may be either out of reach of the HPC system, or compacted enough that they will require rotary XCB or traditional coring. However, HPC targets may be found wherever the Neogene section is reduced or missing.

A minimum of *12 HPC/XCB sites* should be devoted to this program, representing a total of approximately *72 days on site*. This would be in addition to extending many of the Neogene sites mentioned above, which would add about 25% to these time estimates.

Atoll Transects (Priority One)

This program includes :

1. Transects across paired living and drowned atolls (*e.g.* Bikini Atoll and adjoining Sylvania Guyot)
2. An array of three transects along the length of a major atoll chain that extends over a wide latitude and plate age range.

The paired living/drowned atoll transects will each consist of four types of sites described below :

Type A : Archipelagic apron site (two needed in each transect)
- Water depth : ~3000 m
- Penetration : ~800-1000 m of sediment, 100 m of basalt
- Time needed : 8 days (with logging)
- Platform : D/V *JOIDES Resolution.*

Type B : Atoll rim site (one needed)
- On land
- Penetration : 1500 m of limestone, 300 m of basalt
- Time needed : 20 days (with logging)
- Platform : land rig.

Type C : Atoll lagoon site (one needed)
- Water depth : ~70 m
- Penetration : 1500 m of limestone, 300 m of basalt
- Time needed : 20 days (with logging)
- Platform : barge-mounted rig or jack-up platform.

Type D : Drowned atoll site (two needed)
- Water depth : 1500 m
- Penetration : 300 m of limestone, 300 m of basalt
- Time needed : 8 days (with logging)
- Platform : D/V *JOIDES Resolution.*

Total time for D/V *JOIDES Resolution* drilling per transect :
- Site type A (2) = 16 days
- Site type D (2) = 16 days
- Total = 32 days.

Total time for other platform drilling per transect :
- Site type B (1) = 20 days
- Site type C (1) = 20 days
- Total = 40 days.

Total time for entire transect = 72 days.

An ideal array would consist of three transects which would require 96 days of D/V *JOIDES Resolution* drilling and 120 days of other platform drilling. Two transects, provided they could be drilled in optimal locations along an atoll chain, would yield very significant results, and would require 64 days of D/V *JOIDES Resolution* drilling and 80 days of drilling with other platforms.

Passive Margin Transects (Priority One)

Each transect should consist of a minimum of 4 sites in water depths ranging from 200 to 4000 meters.

Each site should have the following operational characteristics :
- double HPC + XCB/RCB
- total penetration of approximately 800-1000 meters
- standard logging.

Occasionally, however, one or more sites may require deeper penetration and could make multiple re-entry a necessity.

The total time required for each of these sites is not as easy to estimate as the time required for the paleoclimate array. But it is clear that a minimum estimate is in the order of 45 operating days for a transect that does not require deep penetration into hard rock (HPC/XCB). If a transect requires penetration into deeper and harder formations, the time required for single bit rotary coring could range from 10 through 18 days per site. An occasional re-entry site will require between 25 and 50 days of operation time. Thus, operating time for a single transect is estimated to range from 45 to 90 days, depending on the nature of the margin.

Conservatively, therefore, we estimate the total time required for three transects as follows :

- 3 HPC/XCB transects 135 days
- 2 deeper rotary (RCB) sites 30 days
- 2 multiple re-entry sites 80 days

which brings the total to *245 operating days (on site)* for this model passive margin drilling program. A minimum of *90 days* of operating time would yield a *single transect* without a full re-entry site.

Arctic Ocean Drilling (Priority One)

At this time it is obviously impossible to determine with any reasonable chance of being accurate the time that will be required for the completion of such a program. It depends on the type of platform that will be used as well as on many environmental factors. The problem is under study by several groups in the US, in Canada and in Europe, and preliminary estimates of the magnitude of such an operation in terms of time and financial investment should be available soon. Prospects about the feasibility of all aspects of the program appear encouraging.

Exploratory Drilling along Continental Margins (Priority Two)

Part of this program might be accomplished by modifying and adding slightly to other drilling programs aimed at solving tectonic problems along passive margins. Some specific sites, however, might have to be planned that would sample critical stratigraphic/lithologic intervals which are still missing for a better understanding of the sedimentary evolution of passive margins.

A total of between 5 and 10 such sites, using HPC/XCB and/or rotary (RCB) techniques, appears a reasonable prospect for such a program (depending on how much can be shared with other projects within ODP).

We can therefore estimate the time required at about *80 days* of drilling operation.

Exploratory Drilling into Older Sediments (Priority Two)

Experience has demonstrated that the oldest sedimentary sequences are very difficult to reach and represent a technological challenge for deep ocean drilling. The deep drilling capability of the *JOIDES Resolution*, believed to represent a major improvement over that of the *Glomar Challenger*, has not yet been tested. Therefore operational data cannot be used to determine with precision the time required to drill into Jurassic sediments of Panthalassa. Based on previous experience with *Glomar Challenger*, a *multiple re-entry site* would require approximately *40 days of operations* (on site). An ideal site has yet to be located. Younger Mesozoic objectives (*e.g.*, black shales) are less difficult, but do pose the problem of adequate recovery in hard-soft sequences. In all, we suggest that *120 days* of operating time be allocated to these objectives.

There is also one important scientific objective, drilling into thick evaporite sequences, which is impossible without new technology (deep-water riser and BOP system).

Technology

Drilling/Coring

The global environmental change program requires a variety of coring techniques that will depend on the sedimentary environments to be sampled. The main emphasis for further developments should be aimed at :

- complete recovery of all types of sediment (including alternations of hard and soft rock)
- minimal core disturbance
- continued improvement of the XCB to achieve the above objectives
- reliable core orientation.

Although riser technology is not essential to drilling on continental margins for the black shale problem, or for other deep drilling objectives, this tool offers an advantage in drill site placement when safety hazards are a consideration. However, it is not clear at this time that acquisition and use of a riser system would be cost-effective. We recommend that a panel broadly representative of the scientific community, including advocates of such a technology and drilling engineers, be convened to consider these questions before future decisions are made in support or rejection of this technology.

Platforms

So far, the community has concentrated on the usage of a single ship that moves from target to target around the world. The increased size of the community involved (both in terms of scientific fields and participating countries) seems to force us to seriously consider a diversification as well as a better adaptation of drilling platforms. A few examples of problems that would benefit from diversification are :

- HPC coring represents at times up to 50 or 60 % (sometimes more) of the operations. This technique certainly benefits from the stability and size of the ship, but does not require such an expensive platform, if smaller core diameter is acceptable.
- Atoll drilling may require the operation of other types of platforms (barges or land-based rigs).
- Arctic drilling will obviously have to be based on a completely different type of platform.

Logging

High to very high resolution sediment logging (*i.e.*, decimeter resolution) offers an exceptional chance to better understand cyclic sedimentary sequences and achieve detailed correlations over the entire world ocean.

Physical-property logging remains the best direct link between geophysics (seismic profiling) and onboard measurements. Both are necessary to construct reliable and precise synthetic seismograms and accurately relate borehole results to seismic reflectors. Such logging also provides high-resolution data that can supplement and extend other laboratory measurements on sediments.

Geochemical logging offers opportunities that have been barely explored, whereas technology has become more and more sophisticated in these domains.

We recommend :

(1) the allocation of sufficient time to downhole log appropriate sites ;

(2) optimization of tool combinations and hole conditioning procedures to speed up logging ;

(3) better coordination and exchange between the scientific community and tool developers ;

(4) improved integration between all onboard programs and downhole logging results.

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Mantle/Crust Interactions

Prepared by WORKING GROUP 2 (see p. 9)

ABSTRACT

The development of plate tectonics coupled with advances in the understanding of mantle convection has gradually led to the realization that the solid earth is a system in active circulation. This circulation includes not only the movement of the plates, but also intricate exchange between ocean crust and seawater through hydrothermal, sedimentary and biologic activity, recycling of material from the earth's surface to the mantle by various mechanisms at subduction zones, and redistribution in the mantle through convection. This circulation has through time created continents and the physical properties and chemical composition of a heterogeneous mantle. The most fundamental geochemical aspects of this cycle are the net flux out of the mantle at spreading centers and the net flux returned to the subduction zone.

To determine these fluxes, it is essential to determine the composition(s) of the bulk ocean crust. Although shallow drilling at diverse locations begins to constrain crustal composition, ultimately drilling through the entire ocean crust is required to determine these net fluxes. Drilling through the entire ocean crust would solve in addition a host of other scientific problems where there are long-standing controversies. These include: the validity of the ophiolite model for ocean crust, the relationship between crustal structure and spreading rate, the origin of the seismically defined stratigraphy of the crust, the compositions of primary mantle-derived melts and how they are modified by magma chamber processes, the total magnetization of the crust and how it is distributed with depth, and the depth and nature of hydrothermal interaction in the crust, with the resultant net flux between crust and seawater.

The drilling of total crustal sections would be a landmark for the ocean drilling program and for geology in the 1990s, and would produce a quantum leap in our understanding of the global plate tectonic geochemical cycle. It is also currently impractical in terms of engineering capability and planning structure. But because of its importance, the first priority of the Working Group is the development of the *capability* to drill through the entire ocean crust by the latter part of this century. "Capability" includes the requisite planning structure, engineering development, and site surveys that will be essential for intelligent site selection in a known geological context, so that the hole can be a calibration experiment for other techniques that can be used to determine lower crustal characteristics in other regions.

Understanding the global system also requires a knowledge of the processes by which interactions among crust, mantle and ocean occur. At spreading centers, it is clear that while ocean drilling is a key element in any program, it cannot proceed in isolation, but should be one part of an integrated program. The integrated program would include (1) extensive bathymetric and geophysical mapping and sampling of the surface; (2) focussed drilling efforts at undersea volcano observatories, including a varied use of the drill holes for geophysical and geochemical logging and as the locations for geophysical experiments; and (3) deeper drill holes down to the sheeted dykes on well-characterized older crust to obtain complete lava stratigraphy to test models of ridge crest segmentation and to determine the net effects of hydrothermal processes in the upper crust. Drilling in and adjacent to fracture zones may allow penetration of plutonic layers of the crust which would complement the holes in the volcanics.

Convergent margins are the key environment exerting control on global fluxes. Outputs to the overriding plate and their variation through time can be investigated by basement drilling and by drilling of clastic aprons in both the back-arc and forearc. Inputs to the mantle are key unknown pieces of information essential for evaluating models of mantle heterogeneity that rely on recycled components from subduction zones and models of the sources of arc volcanics. On the down-going plate, several holes that penetrate at least through the zone of greatest hydrothermal interaction are essential. These holes should be located on older oceanic crust adjacent to well-studied oceanic island arcs. The possible relationship of subducted compositions to arc volcanic compositions can be investigated by a series of holes outboard of arcs that exhibit systematic variation along strike.

A final important series of objectives relates to mantle convection and the time-integrated effects of the plate tectonic geochemical cycles. In analogy with magnetic anomalies of the ocean crust carrying a record of secular variations in the earth's magnetic field, the basaltic ocean crust contains a chemical and isotopic record of mantle convection. Mapping of crustal composition can provide quantitative information about the size, distribution and compositions of mantle reservoirs and the efficiency of convective stirring. This information could provide a test for geophysical models of mantle convection. In some specific settings, such as where ridges and hot spots interact, geochemical mapping can also directly reveal mantle kinematics. In addition, the longevity of geochemical signatures of rising mantle plumes or hot spots will provide important clues for the convective isolation of mantle reservoirs. Dating of hot spot chains can provide evidence for their relative motion which provides in turn boundary conditions for the dynamics of mantle convection. There are also important components of global fluxes, such as oceanic plateaus and seamounts not associated with clear hot spot tracks that are virtually uninvestigated and may have a unique and important place in the global circulation system. These various problems can be investigated by an extensive program of geochemical mapping using many holes with shallow basement penetration. Most of such a program could be carried out with a smaller drilling platform capable of limited basement penetration.

INTRODUCTION

The title given to Working Group 2 by the COSOD II Steering Committee was "mantle-crust interactions", which we

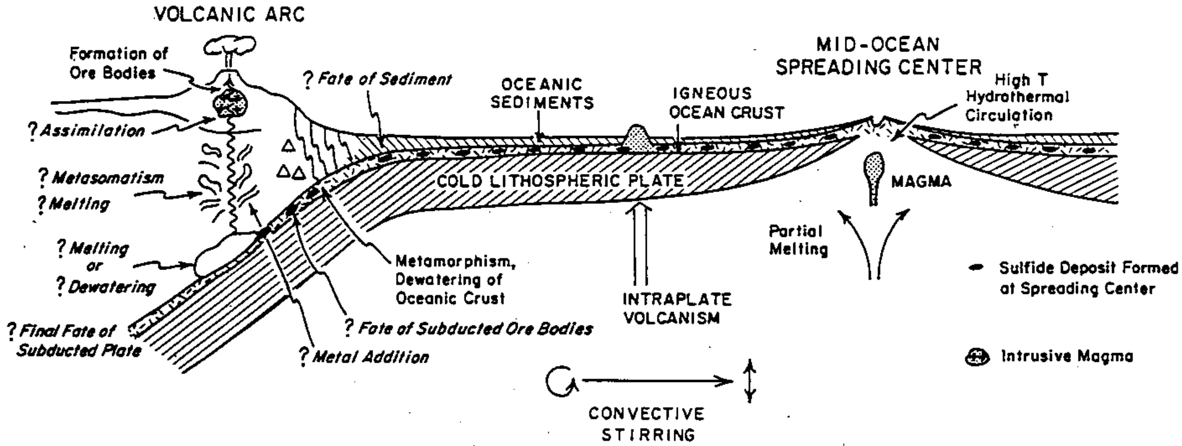

Figure 1. Cartoon of the plate tectonic cycle showing some of the fluxes, and the processes that control the fluxes.

have taken to encompass the present systematics of the solid earth, plate tectonic geochemical cycle and the record of its past action as revealed in the ocean crust. It is important to note at the outset that this thematic mandate is distinct from that given to the Lithosphere Panel of the present ODP planning structure, or to the COSOD I Working Group on "Origin and Evolution of the Oceanic Crust", and does not include hydrothermal problems. The emphasis of this report is on how to investigate the general thematic problems of the circulation of the solid earth, and the primary differentiation of crust and mantle that this circulation has brought about through time. This document grew out of a "white paper" prepared by the members of Working Group 2, but that white paper has been substantially modified as a result of the oral discussion at COSOD II and the many written contributions from participants in COSOD II and from other interested scientists.

The Thematic Framework : Solid Earth Geochemical Cycles

The development of plate tectonics coupled with advances in the understanding of mantle convection, exploration of the ocean floor and the development and application of precise geochemical techniques has gradually led to the realization that the solid earth is a system in active circulation. This circulation includes not only the movement of the plates, but also intricate exchange between ocean crust and seawater through hydrothermal, sedimentary and biologic activity, recycling of material from the surface to the mantle by various mechanisms at subduction zones, and redistribution in the mantle through convection prior to the return to the surface through volcanism at divergent margins, convergent margins, or intraplate settings. This circulation, or possibly a variant of it, has through time created continents, ocean basins, the physical properties and chemical composition of a heterogeneous mantle, and to a significant extent the chemical balance of seawater. "Mantle/crust interactions" might be termed "solid earth geochemical cycles", for the term "geochemical cycles" is now as apt for solid earth circulation as it is for surface circulation, and entails the same close connection between chemical fluxes and physical properties.

In this sense, the questions that are beginning to emerge are akin to those of Working Group 1 concerning the climate system, for once the solid earth is viewed as a system in circulation, then an understanding of that system requires knowledge of the material and energy that are transferred among the parts of the system. What are the fluxes between different reservoirs ? What processes control the fluxes ? How have the fluxes varied through time ? Can we predict the fluxes with quantitative physical models, and test the models through carefully planned data collection ? Addressing these questions is necessary for understanding the wider implications of plate tectonics and how the solid earth works. At the moment, however, there is a decided lack of data concerning many aspects of solid earth circulation.

Consider the first order fluxes and the data available concerning them. Figure 1 conveys the general problem in terms of the plate tectonic cycle. A convenient point of entry into the cycle is plate formation at spreading centers. Melt is generated by mantle upwelling at ocean ridges, and the emplacement of the melt in the crust causes vigorous hydrothermal circulation through which chemical exchange occurs between seawater and the new igneous crust. What is the bulk composition of the crust prior to the chemical exchange ? We can infer it by several theoretical methods, but there is not a single definitive data point.

As the crust ages, both oceanic and continental detritus accumulate on it and there continues to be exchange via fluids between the igneous and sedimentary portions of the crust and the ocean. The crust may be affected by intraplate volcanism and thereby thickened and chemically modified. As the crust approaches a convergent margin, a significant component of sediment from the arc may be deposited, both from erosion of the overlying plate and from deposition of air fall from volcanic eruptions. This package of material then enters the subduction zone. What is the bulk composition of the subducted crust and how does it vary spatially in the oceans ? What is the net exchange between crust and seawater, and how is it dependent on spreading rate and tectonic setting ? Again, there are inferences but no definitive data.

Some portion of the subducted mass is transferred to the overlying arc through accretion, subcretion and volcanism ; some may be transported via dehydration up the slab into the forearc or the ocean or into the mantle wedge ; and the majority of it is recirculated into the mantle through convective mixing, presumably to reemerge either at hot spots or at ocean ridges. The processes of circulation thus exert control on the composition and organization of continents and of the mantle.

Time-Integrated Effects of the Geochemical Cycles

The time-integrated action of solid earth geochemical cycles has created the fundamental differentiation of the earth. Part of the record of that differentiation is preserved in the continents ; an equally important record exists in the upper mantle as well. Although all ocean crust is relatively young, it provides a window into old mantle, and the nature and distribution of various mantle compositions provides clues to how the earth has evolved and how the mantle is organized. The ocean crust may also record in certain areas the interaction between various mantle reservoirs, and hence place constraints on the movement and interaction of the reservoirs.

Thus the record of the effects of plate recirculation in the mantle, the nature of convective mixing, and other possible variations in mantle composition are indirectly recorded in the chemistry of the ocean floor. A map of ocean floor chemistry could in many ways be converted into a map of some aspects of mantle composition. But we are nowhere near having such a map. The composition of the ocean floor has for the most part been explored only by dredging parts of a single line defined by spreading centers, supplemented by studies of ocean islands.

General Scientific Objectives

Mantle/crust interactions occur in diverse settings and through a variety of processes, and are intimately connected to the plate tectonic cycle and mantle convection. The objectives associated with mantle/crust interactions that can be addressed by drilling can be divided into the following three thematic categories :

(1) *Global Geochemical Fluxes*. Our current knowledge of fluxes is primitive. Although many people have estimated the composition of fresh oceanic crust, these estimates have never been directly tested ; the bulk composition of altered ocean crust and its variability are widely agreed to be unknown.

(2) *Magmatic and Tectonic Processes that Control the Fluxes*. As part of understanding the global geochemical cycle, it is also important to know the processes by which interactions among crust, mantle and ocean occur. This requires knowledge of the magmatic and tectonic processes occurring at divergent and convergent margins, and at intra-plate locations.

(3) *Mantle Dynamics and Composition*. Although all ocean crust is young, it provides a window into old mantle. The ocean crust may also record in certain areas the interaction between various mantle reservoirs, and hence place constraints on the movement and interaction of the reservoirs.

The Role of Drilling

Aspects of each of these three scientific themes can be addressed by ocean drilling, but, more importantly, there are some crucial data that can be obtained only by drilling. Some of the data can be obtained using existing drilling techniques. Geochemical mapping of the ocean floor to investigate mantle dynamics and composition, for example, requires a large number of drill holes with shallow basement penetration. But for the most part, the crucial data require information from more than the top few percent of the crust. The domain in which these questions must be investigated requires technically difficult and time-consuming, deep crustal penetration.

Although regional drilling at various places around the globe with relatively shallow penetration continues to provide important data for the earth sciences, there is now some risk that continuation of a similar program will asymptotically reach a level of ever smaller scientific returns. Such a program will not produce the crucial data that are needed for a substantial increase in our understanding of mantle/crust interactions. We suggest that the time has come to intentionally aim at major drilling objectives that carry the promise of increasing our understanding of global dynamics by a large step. These objectives are :

(1) To develop the capability of deep crustal penetration, with the ultimate long-term goal of drilling through the entire ocean crust to obtain total crustal sections.

(2) To constrain mantle composition and dynamics by geochemically mapping the ocean floor with a large number of shallow drill holes.

(3) To investigate the processes of sea floor spreading by drilling into older crust in well-surveyed areas of known tectonic setting, and to investigate active spreading center volcanoes in conjunction with the establishment of "natural laboratories."

(4) To study the evolution of convergent margin volcanoes and convergent margin fluxes by holes of shallow and intermediate depth on both the down-going and over-riding plate.

These four objectives are discussed in greater detail in the following sections.

The Roles of Technology and Planning

There is no question that a further decade of drilling leading to a few more holes with a few hundred meters of basement penetration could lead to an improvement in our understanding of certain aspects of mantle/crust interactions. But to take a truly substantial step towards the thematic objectives outlined above seems to require two things that have nothing to do with enunciating scientific priorities : the capability of long-term planning and the application of substantial resources to technological objectives. To attain the scientific objectives it will be necessary to advance deep sea drilling technology so that both deep penetration holes and rapid, multiple shallow hole drilling become feasible within the next several years. The past history of both DSDP and ODP shows that deep penetration is very difficult using the current drilling methods. Figure 2 shows the progress in drilling the deepest basement penetration to date at Site 504B. The number of days necessary for a given penetration interval increases exponentially. Blind extrapolation would suggest that another seventy days of drilling (two legs) would lead to only 335 more meters of penetration, provided the hole does not have to be abandoned because of drilling conditions. The seismic data suggest that layer 3 may be about 450 meters below the current depth. Furthermore, current drilling methods, which essentially grind their way through the crust, provide very limited recovery, which severely limits the scientific utility of the hole. It is likely that what is recovered is not representative since soft lithologies are likely to be destroyed by the drilling process. Therefore, even given the dedicated use of the *JOIDES Resolution* and a planning structure able to undertake and guide large projects of long duration, the prospects for truly deep basement penetration with present drilling technology are not promising. Thus the accomplishment of the highest priority scientific objectives enunciated in this report will not be possible without a substantial new effort in technological development.

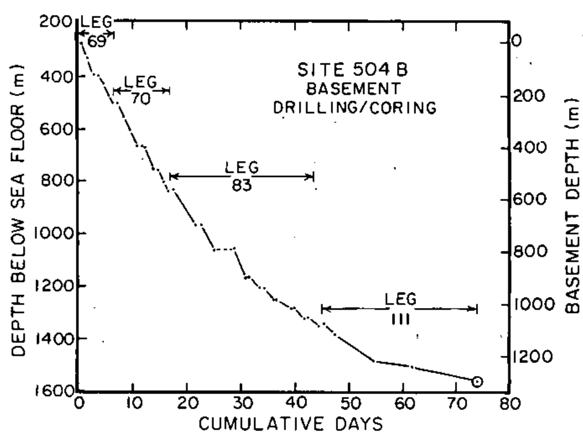

Figure 2. History of drilling/coring operations at Site 504B. Cumulative time does not include that used for logging and downhole measurements, but does include drill string round trips for bit changes and for fishing caused by equipment failures. Data from Initial Reports of the DSDP, except for preliminary shipboard report for Leg 111. Figure courtesy of J. Von Herzen (personal commun.)

THE CAPABILITY OF TOTAL CRUSTAL SECTIONS: A LONG-TERM GOAL

The General Importance of Crustal Composition to Plate Tectonic Geochemical Cycles

The ocean crust covers 60% of the earth's surface, and is the principal medium through which interaction between the mantle and the earth's surface, including the hydrosphere, takes place. The creation and destruction of the ocean crust is the clearest manifestation of solid earth dynamics, and it has fundamental implications for the chemical and thermal evolution of the earth and the buffering of ocean chemistry. The importance for the evolution of the earth's mantle is apparent from the fact that, at the current production rates, a mass equal to most of the earth's mantle could have been processed through spreading centers in the past 4 billion years. Ocean crust recirculated into the mantle may account for more than 10% of the current mantle mass, and has been suggested as the source of some hot spots (*e.g.* Hofmann and White, 1982). Thus processing associated with crust formation and subduction extensively influences mantle evolution and composition. The nature of that influence depends in part on the composition of material removed from the mantle to form the crust, and on the modified composition returned to the mantle.

Formation of ocean crust at ridges also controls many aspects of the chemical and isotopic composition of the oceans. Fluxes from the ocean ridges through hydrothermal activity and into the ocean crust through low and high temperature reactions with the basement are large components of the mass balance of ocean chemistry. Many questions concerning global geochemical cycles at the earth's surface cannot be adequately answered without knowing the composition of the ocean crust before and after it has interacted with seawater. Knowledge of altered crustal compositions is also important for understanding volcanism at convergent margins. Almost all models for such volcanism call for a contribution from the subducted ocean crust, and lack of knowledge of the compositions of that crust inhibits quantifying the models. The net fluxes at convergent margins may have controlled not only mantle chemistry but continental crust formation as well.

The ocean crust composition, therefore, is central to any investigation of the solid earth geochemical cycle, and to investigation of cycles involving the hydrosphere as well. Despite its central importance, present sampling of the ocean crust is limited to the upper kilometer, and even in these sections the recovery of rock has usually been substantially less than 50%. Although the arguments relating to the importance of the ocean crust composition refer to ocean crust in general, we should not lose sight of the fact that ocean crust is not of a single, constant composition, but is quite variable. It is produced in subduction zone environments at back-arc spreading centers as well as at mid-ocean spreading centers; it is formed at a variety of spreading rates and by mantle that may vary in potential temperature by 200 degrees. The crust will also have short wavelength variability due to along-strike variation in hydrothermal activity and the locations of transform faults and other ridge offsets. For these reasons it is necessary in the long-term view to realize that several separate determinations of total crustal composition will ultimately be necessary, and, most importantly, that the holes should be used to test models and to calibrate indirect methods of measuring aspects of total crustal sections in order to minimize the number of sections that will be necessary.

Specific Scientific Controversies that Could Be Resolved with Total Crustal Sections

The first order scientific returns of total crustal sections will be the capability to compare crustal structure to seismically defined layers, to infer fresh, unaltered composition and to determine bulk, altered composition. These objectives are essential for beginning to constrain global geochemical fluxes, for understanding the true meaning of the seismic layers which currently define ocean crust, and for understanding the magmatic and tectonic processes by which ocean crust is made. Sections through the entire crust would also provide specific and definitive answers to major outstanding questions concerning the ocean crust:

(1) ***How do ophiolites compare with "normal" ocean crust?***

A major source of our present ideas of crustal stratigraphy comes from the study of ophiolite complexes, which have been traditionally regarded as the model for "typical" ocean crust (Fig. 3). Indeed, most of what we understand of crustal stratigraphy is based upon that of recognized complete ophiolite sequences, since only one hole (DSDP 504B) has successfully drilled oceanic layer 2B. Drilling at DSDP Hole 504B has confirmed part of the ophiolite analogue in the presence of the sheeted dyke unit (*e.g.* Anderson, Honnorez *et al.*, 1982). However, the correlation of deeper structures of the oceanic crust with that mapped in ophiolite terrains has yet to be verified by deep crustal drilling.

In light of recent detailed chemical, mineralogical and structural studies of a number of well-preserved ophiolite suites, two central questions arise concerning the ophiolite analogue:

1) Do ophiolites represent oceanic crust produced at a typical ridge spreading center or are they samples of oceanic crust produced in other environments?

2) Even if they are from environments of formation that are not the same as modern ocean ridges, are they sufficient analogues, in the sense that their overall stratigraphy resembles the gross stratigraphy of normal ocean crust, and the processes that produced the stratigraphy are similar in both cases?

Studies of the chemistry and mineralogy of ophiolite extrusive sequences suggest that many classic ophiolites are

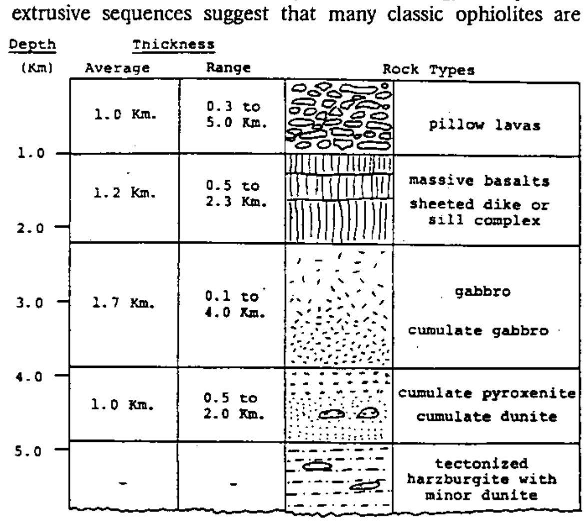

Figure 3. Igneous stratigraphy of typical ophiolite. Thickness data are from Moores and Jackson (1974). Inferred thicknesses, particularly for the gabbros and below, rely on assumption that foliation and banding seen in outcrop are parallel to large-scale lithologic layering (W. Kidd, 1976, written commun.). Note that section shown is inferred unmetamorphosed section. In most ophiolites, pillow basalts and sheeted dyke complex are metamorphosed to greenschist or amphibolite facies, and cumulate and tectonized ultramafic rocks are partially to totally serpentinized. There is often an extensive shear zone between cumulate and tectonized ultramafic rocks. From Clague and Straley (1977).

more closely related to an arc or near-arc setting (supra-subduction zone) rather than to a typical mid-ocean ridge spreading center (*e.g.* Miyashiro, 1973 ; Saleeby, 1982 ; McCulloch and Cameron, 1983). Although the chemical evidence is persuasive, the classic ophiolite definition and ocean crust analogy are based upon stratigraphy and overall lithologic associations. To date these are not well defined in any oceanic environment. Indeed, recent reinterpretations of ophiolite structure and stratigraphy indicate that complex interactions of magmatism, deformation and high-temperature metamorphism may occur synchronously during oceanic crustal formation and that simple "magma-chamber" models, used frequently by workers on *in situ* oceanic crust, may be in error.

It is also noteworthy that ophiolites can be of very different thicknesses, in contrast to the remarkably uniform thickness of seismically defined ocean crust. Serpentinized mantle peridotites are not rare in the upper crustal levels of the mid-Atlantic ridge, in conflict with classic ophiolite stratigraphy. Layers of peridotite and gabbro rubble interbedded within the very first few hundreds of meters of pillow lava flows were cored in several holes along the MAR during Legs 37, 45 and 82, indicating that deep crustal and mantle rocks were outcropping along submarine cliffs in the immediate vicinity of the holes. In 1986, during Leg 109, outcrops of mantle peridotites were discovered by a diving team using the *Alvin* submersible on the western flank of the rift valley of the MAR, some 40 km south of the Kane Fracture Zone. These peridotites were drilled and cored over 100 m without the support of sediments or a guide base (using an hydraulic motor), and appeared to be strongly foliated, typical mantle harzburgites. The ophiolite analogue in this case may be found in some ophiolites in the Alps and Apennine, where all reconstructions indicate that this upper-Jurassic ocean basin was mainly floored by peridotites and gabbros, overlain by discontinuous patches of basaltic flows. This model, probably useful for slow spreading ridges, is of course extremely different from the "Penrose Conference-type ophiolite model", which may apply for fast-spreading ridges (Hole 504B, for example). But if the petrologic structure is so variable as a function of spreading rate, why is seismically determined crustal structure so uniform ?

Thus, it is important to recognize that there are several ophiolite hypotheses for oceanic crust, and that none of them have been adequately tested. Even if the general "ophiolite model" is correct, it is important to calibrate it in the actual ocean crust with respect to spreading rate and other tectonic parameters.

(2) ***What is the actual stratigraphy of the ocean crust, and how does it relate to the seismically defined crustal layers ?***

The layers of the ocean crust are currently defined only seismically, and it is seismic data that have established the ocean crust as an identifiable worldwide feature, and shown that it has an apparently remarkably uniform structure (*e.g.* Christensen and Salisbury, 1975 ; Ewing and Houtz, 1979 ; Spudich and Orcutt, 1980). But what do the seismically defined layers represent ? Seismic velocities in the oceanic crust vary in response to changes of lithology, porosity, fracture density and metamorphic grade. Traditionally, seismic stratigraphy is interpreted with respect to the important boundaries of the ocean crust inferred from ophiolite studies. There are the extrusive-dyke boundary, the gabbro-dyke boundary, and the Moho. Comparisons of the inferred velocity structure of complete ophiolites with seismic boundaries from ocean crust (Fig. 4) have suggested a good correspondence between the two (Salisbury and Christensen, 1978). However, only the shallowest boundary between extrusive units and dykes has thus far been identified in *in situ* oceanic crust at Hole 504B. Thus the actual meaning of the seismically defined boundaries remains unclear.

It is also important to determine the actual crustal thickness to determine if it can be accurately measured seismically. Recent thermal and petrological models of melting in the mantle provide predictions of petrologically defined crustal thickness (Klein and Langmuir, 1987) - but the relationship between the petrological crustal thickness predicted by the thermal models and the measured "crustal thickness" of the seismic studies is not clear.

Improvements in geophysical techniques will enhance existing capabilities for mapping and remote characterization of seismic boundaries in the ocean basin. The value of these measurements, however, will be severely limited unless the ground truth data are available to validate and calibrate geophysical interpretations. The use of boreholes to define the nature of seismic reflectors which can then be mapped over large areas by reflection profiling is a powerful technique used in the study of sedimentary stratigraphy on land and in the ocean. The same approach must be applied to the igneous crust. Although drilling of igneous rocks is slow and expensive it can provide unequivocal geological and physical property information in "type" localities which can then be extended using various geophysical methods.

(3) ***What are the compositions of primary mantle-derived melts and how are they modified by magma chamber processes ?***

The oceanic crust is constructed from mantle-derived melts and a total vertical mass balance of this crust would yield the composition of the parental melt that crosses the mantle/crust interface (Malpas, 1978 ; Elthon, 1979). There is no other way of conclusively determining this composition, which has implications for mantle temperature, processes of melt segregation, and the contentious issue of how radical are the effects of fractionation processes in magma chambers (*e.g.* O'Hara, 1977). This information would provide essential information for the longstanding petrological controversies over the composition of melts delivered from the mantle and the effects of low pressure magma chambers on erupted compositions, and would allow inferences to be made concerning the degree of melting of the mantle that gives rise to ocean crust, and the depth or range of depths where this melt originates. A detailed chemical stratigraphy of the cumulates would also allow inferences to be made concerning the number of discrete inputs of magma to a crustal reservoir, and the processes of crystal fractionation that occur within the reservoir. It is important to obtain such stratigraphy from normal ocean crust because stratigraphic studies of some ophiolite cumulates have shown that it is difficult to relate the cumulate compositions to those of common ocean ridge basalt liquids erupted on the sea floor (Komor *et al.*, 1985). If this proves true in normal ocean crust, it will substantially modify views of ocean crust magma chambers and the fractionation that they can produce. A comparison of erupted lavas and dykes to cumulate compositions from a single drill hole would also be in a general sense a unique and classic petrologic data set with which to evaluate magma chamber processes.

(4) ***What are the depth and nature of hydrothermal interaction in the crust, and the resultant net flux between crust and seawater ?***

There is considerable debate concerning the net effect of hydrothermal activity on the chemistry of the oceans (Edmond *et al.*, 1979 ; Hart and Staudigel, 1982). Large fluxes exist at black smokers, but much of this flux is taken up by low temperature alteration in the upper crust. How do these two competing effects balance out ? To determine this, the bulk composition of the crust and the distribution of elemental abundances with depth must be determined.

The depth of penetration of hydrothermal activity in the crust is central to evaluating the hydrothermal circulation pattern at ridges (and by inference the nature of crustal magma chambers) and the mechanisms of heat removal from the crust. The depths of high and low temperature hydrothermal penetration are currently unknown. The depth and nature of the hydrothermal alteration are central to evaluating the questions of crust/mantle and crust/ocean interaction.

(5) ***What is the bulk composition of subducted ocean crust, and is it a suitable source for arc volcanics and for some hot spots ?***

Subduction carries ocean crust and a portion of its sediment cover back into the mantle. Some material is released by poorly understood processes into convergent margin magmas, and the rest is subducted to greater depths. This process must modify the chemistry of the mantle to the extent that what is subducted is different from what is removed at spreading centers. Moreover, the hypothesis that subducted ocean crust can later give rise to some if not all hot spots (*e.g.* Hofmann and White, 1982) depends critically on the parent/daughter ratios of the various radiogenic isotope systems in the subducted crust. This is particularly important for the Th-U-Pb system, since the vertical distribution of these elements in the ocean crust is strongly affected by alteration processes (*e.g.* Chen *et al.*, 1986). Understanding both the role of subducted crust in island arc and intraplate settings, and the chemical fluxes from mantle to crust and back into the mantle, requires a rigorous estimate of the bulk composition of ocean crust.

Finally, we note that any drill hole into previously unexplored depths always carries the hope and potential of unexpected but major serendipitous discoveries. We therefore believe that we should recognize the value of exploring the unknown. Not only in plate tectonics but also in many other areas of science, the major breakthroughs in knowledge and understanding often come from totally unexpected discoveries. We do not know what we may find if we can drill a complete crustal hole but the information that would be gained from this long-held goal of the geoscience community is essential for an understanding of mantle/crust interactions.

Drilling Strategy and Problems of Implementation

The ability to drill total crustal sections would be a landmark for the Ocean Drilling Program (ODP) and for the understanding and quantification of the global plate tectonic geochemical cycle. In terms of cost, the need for engineering development, and the need for long-term planning, it is of a different order than the other objectives presented in this report or drilled by ODP in the last three years. It is not the sort of project for which the proposal-driven, eclectic planning structure of ODP was designed. Furthermore, a comprehensive strategy for obtaining the objective requires an interface between scientific goals, planning structure, engineering possibilities and funding realities that cannot be accomplished in a format such as COSOD II. Certain general aspects, however, seem clear. It would be desirable to have a total crustal section on crust formed at a slow and a fast-spreading ridge, since comparison of crustal structure for the two end-members would resolve many outstanding questions concerning the significance of spreading rate to crust formation processes. The hole should be on old crust that has experienced all the various chemical modifications. Old crust also has the major advantage of being colder at depth. The scientific context of total crustal sections is also crucial, and site locations should be extensively debated. Exhaustive site surveys are necessary, or much of the utility of total crustal sections would be lost. To this end, there should be geophysical, geochemical and bathymetrical studies to provide the most complete surveying of the areas proposed for the deep holes. Such associated programs would need to be implemented in the near term in order to prepare the ground for truly deep crustal drilling. The capability of deep crustal penetration will require a major engineering effort dedicated to developing new techniques both to improve recovery and to increase drilling rates. It would seem sensible for such a development program to be independent of the on-going engineering problems associated with taking care of leg-by-leg difficulties. The engineering development should have a time table, ship time for testing, and be overseen by scientists. Initial planning would need to commence immediately to put the ultimate goal of total crustal penetration within reasonable reach during this century. Aims of the planning would include developing the necessary site surveys to make the few ultradeep holes of maximum utility and to provide the links between scientific needs and engineering development. For example, how much would the science be compromised if the hole had a diameter of only a few centimeters in the lowermost kilometer when it penetrated the Moho ? Finally, the hole should be used as a laboratory as it is drilled and after it is drilled, both for *in situ* measurements of crustal properties and also for the calibration of tools, such as vertical seismic profiling, that could be used to estimate deeper crustal properties using shallower holes.

It would be unwise as well as impractical to argue for the devotion of the total resources of the engineering group or the drilling platform to a crash program of development at the expense of investigating other high scientific priorities. Nor will it be possible that a complete crustal penetration, the ultimate goal, will be achieved in the near future. We therefore subscribe to a program of successive attempts to drill progressively deeper holes within reasonable time intervals, at geologically and tectonically important sites where even moderate penetration will provide answers to important geological questions.

Recognizing that it is unrealistic to plan for immediate success in drilling to the mantle boundary with good recovery and high drilling rates, we recommend that the following goals be set :

By 1992 - Routine drilling, with a minimum of 75% recovery to depths of 1000 meters below the basement/sediment interface ;
By 1996 - Drilling to 3000 meters, well within layer 3 ;
By 2000 - Drilling to Moho.

It may be worth noting that if there could be reliable side wall coring with good depth control, then the importance of recovery could be circumvented.

MANTLE COMPOSITION AND DYNAMICS

Introduction

Convection and melting in the mantle have produced a unique physical and chemical record in the basaltic rocks of the ocean basins. It was the reading of part of this record, the dating and mapping of magnetic anomalies, that provided some of the key evidence for the theories of sea floor spreading and plate tectonics. In addition to the "tape recording" of magnetic anomalies, the basaltic ocean crust, including intraplate volcanoes, contains a chemical and isotopic record of mantle convection. This record can be read, albeit imperfectly, using the compositions of basalts formed at mid-ocean ridges (MORB), islands, seamounts and plateaus. MORB and other oceanic basalts reveal information concerning the kinematics of mantle motions as well as the integrated results of past geochemical fluxes that can be obtained in no other way.

Over the past fifteen years intensive dredging programs along the ridges have greatly improved our knowledge of the variations in the composition of the upper ocean crust and the underlying mantle. Early studies demonstrated that ocean island basalt sources were consistently different from those of MORB (*e.g.* Gast, 1968), and this was an important constraint

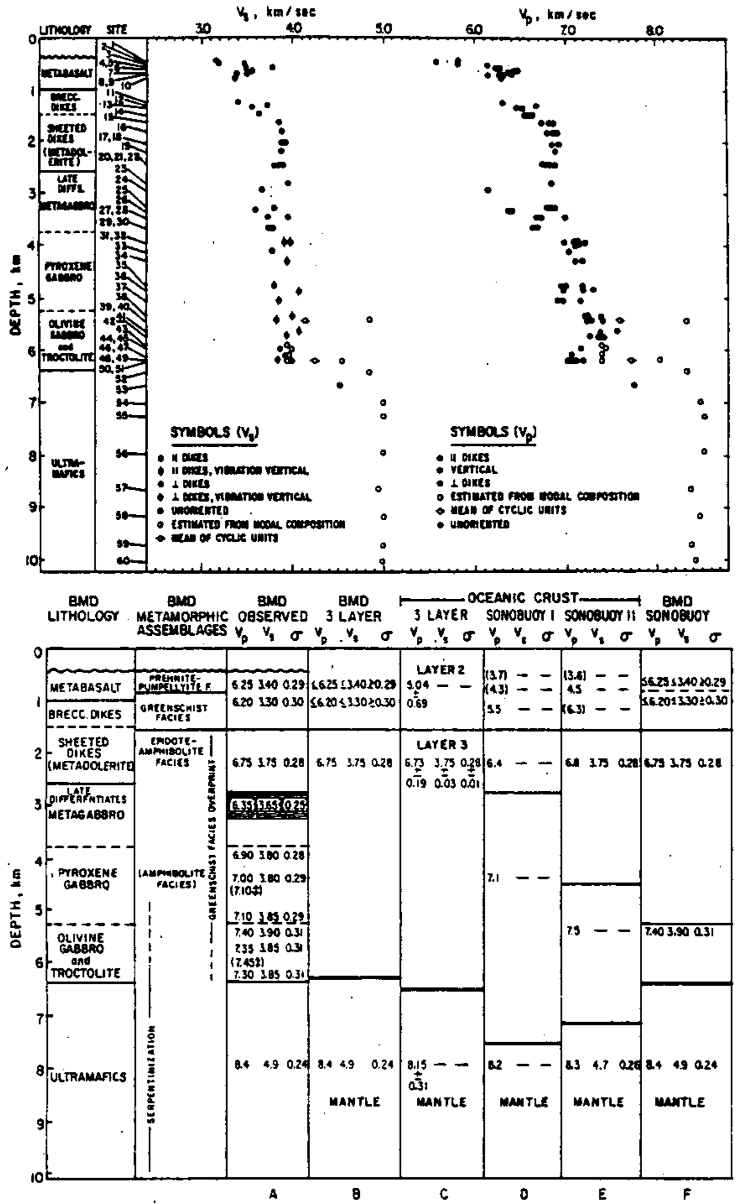

Figure 4.

(a) Compressional (*Vp*) and shear (*Vs*) wave velocity data as a function of depth in the Blow-Me-Down massif.

(b) Comparison of the petrology and seismic velocity structure of the Blow-Me-Down (BMD) massif with the velocity structure of the oceanic crust. Column A is the seismic velocity structure of the Blow-Me-Down massif as reconstructed in the laboratory ; column B, as seen by classical refraction techniques ; and column F, as seen by sonobuoy techniques. Column C is the oceanic seismic velocity structure (after Christensen and Salisbury, 1975), as seen by classical refraction ; and columns D and E, as seen by sonobuoy techniques. The arrows after values indicate propagation velocity for vertical direction. The heavy line indicates the Mohorovičić discontinuity.

From Salisbury and Christensen (1978).

on the development of current ideas on the origins of hot spots. Further work along the strike of spreading centers has shown that there are regional gradients around many hot spots (*e.g.* Schilling *et al.*, 1983). It is also now recognized that, even within normal MORB, there are geochemical variations that can be mapped. For example, isotopic differences are emerging among the different ocean basins, at least for very young basalts, suggesting that the depleted upper mantle consists of a number of distinct subreservoirs produced by a variety of processes (*e.g.* Ito *et al.*, 1987 ; White *et al.*, 1987 ; Dupré and Allègre, 1983)(Fig. 5).

It is tempting to put all discussion of mantle composition and dynamics into the paradigms of plate tectonics and hot spots. But there are substantial pieces of the ocean floor that need to be included in the larger picture that are not readily fit into these paradigms. Seamounts, oceanic plateaus and other intraplate volcanic events such as off-axis sills that produce anomalously shallow acoustic basement contain equally intriguing parts of the mantle convection record. The chemistry of small seamounts formed near ocean ridges resembles partly that of ocean ridge basalts and partly that of ocean island basalts (Batiza and Vanko, 1984 ; Zindler *et al.*, 1984). Many other intraplate seamounts have compositions very different from MORB. Dating one chain of seamounts (the Hawaiian-Emperor chain) has already given us one major breakthrough : by confirming the hot spot hypothesis with remarkable precision, it has pointed the way to an understanding of mantle plumes (Fig. 6). But the Hawaiian chain appears anomalous in the context of the vast majority of Pacific seamounts. The submerged, old expressions of other ocean islands hold the key to questions of the longevity of hot spot geochemical signatures. We also know far too little about the ages, compositions and significance of the thousands of smaller and apparently isolated seamounts that litter the sea floor.

Oceanic plateaus are also important yet enigmatic features. It is now realized that the volumes and rates of formation of some of the plateaus are analogous to continental flood basalts. Many continental flood basalts have a distinctive major element chemistry which indicates the possibility that their source materials are substantially enriched in pyroxene compared to upper mantle peridotites. If this is the case for the materials of the oceanic plateaus, then we may expect heterogeneity in terms of mineralogy as well as trace element chemistry in the mantle source region, which would imply in

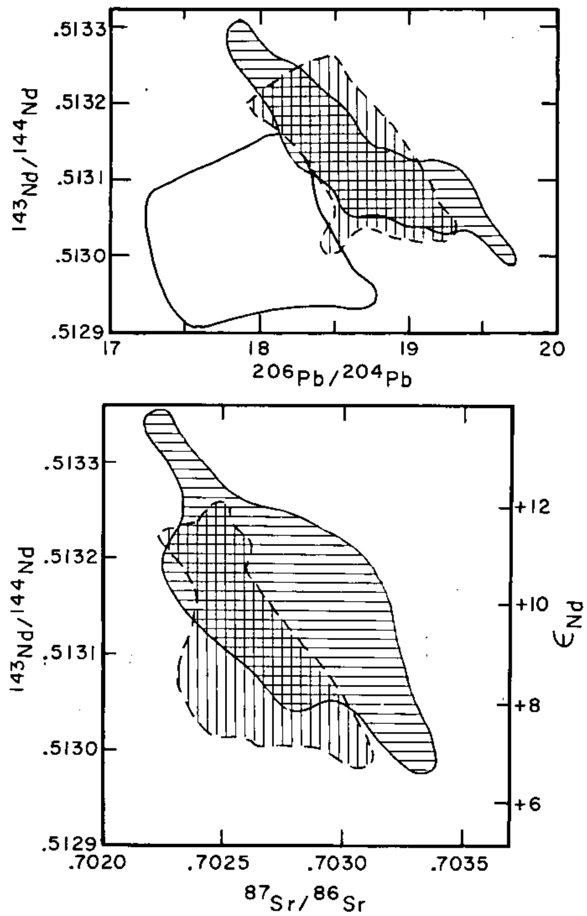

Figure 5. Isotopic compositions of MORB from the Atlantic, Pacific and Indian Oceans; modified after Ito et al. (1987). Atlantic field is hatchured horizontally, Pacific field is hatchured vertically, Indian Ocean field is shown only in the Nd-Pb figure and has no hatchures. One outlying Pacific data point is omitted from the Pacific field in both plots. Note that Indian Ocean MORB have lower $^{143}Nd/^{144}Nd$ for the same $^{206}Pb/^{204}Pb$ compared to Pacific and Atlantic MORB. Note also that, on a statistical basis, Pacific MORB have lower values of $^{143}Nd/^{144}Nd$ for a given $^{87}Sr/^{86}Sr$ compared to Atlantic MORB, although the two oceans show complete overlap in terms of $^{143}Nd/^{144}Nd$ - $^{206}Pb/^{204}Pb$.

turn that these plateaus have a unique and important place in the global circulation system.

Most of the geochemical record away from the ridges is concealed beneath sediments, and hence this record is accessible only by drilling. As a result, more than 95% of the available data come from the zero-age perspective of the youngest ocean ridges, or from recent basalts from ocean islands. Geochemists have had to infer the pattern of mantle heterogeneity from a one-dimensional line through a complex pattern, and the line does not cross some of the most important oceanic features. We are trying to understand large mantle structures, but little is known about the geochemical variability of the ocean crust in plan view, the scale of variations with time, or of the temporal variability in the chemistry of hot spot or ocean ridge volcanism. If the chemical record of ocean crust chemistry could be extended in time and space by preparing a geochemical map of significant portions of the ocean floor, the kinematics of mantle convection would be revealed in much the same fashion as magnetic anomalies have revealed the kinematics of sea floor spreading.

Mapping Mantle Reservoirs

Implications for Convection

The overall organization of geochemical reservoirs in the mantle, once determined, would be a primary observation that all models of convection would have to account for. The data currently available reveal mantle domains on a variety of scales: (a) features the size of ocean basins, such as the Indian Ocean isotopic province and the "Dupal" anomaly (*e.g.* Dupré and Allègre, 1983 ; Hart, 1984) (Fig. 7) ; (b) regional gradients with a scale length of 1000 km, such as that observed in the north Atlantic in the vicinity of Iceland and the Azores islands, that correlate with the bathymetry of the ridge (*e.g.* Schilling *et al.*, 1983) ; (c) coherent geochemical gradients or anomalies at smaller scales, on the order of 100-300 km, sometimes correlated with a bathymetric anomaly (*e.g.* at 14°N and 35°N on the mid-Atlantic ridge) (*e.g.* Shirey *et al.*, 1987), and sometimes with little or no bathymetric anomaly (*e.g.* at 15°S on the mid-Atlantic ridge (Hanan *et al.*, 1986)) ; (d) local heterogeneities over less than 10 km, such as occur at some seamounts, along some portions of the East Pacific Rise and in some drill holes where there is substantial variation in radiogenic isotopes and trace elements in a very small area (*e.g.* Zindler *et al.*, 1984 ; Langmuir *et al.*, 1986). With respect to all of these heterogeneities, Zindler and Hart (1987) have shown that the compositional amplitude of the heterogeneity is positively correlated with the length scale of inspection (Fig. 8).

This documentation of a variety of scales of mantle heterogeneity has led to many diverse ideas concerning the location of heterogeneous domains within the mantle. The idea of "primordial" mantle plumes implies large, uniform reservoirs isolated from the upper mantle reservoir. Alternatively, blobs of different sizes could be distributed more randomly throughout the mantle. Theory and numerical calculations suggest that mantle convection is very efficient in stirring the mantle so that chemical heterogeneities should not survive for more than a few hundred million years (Hoffman and McKenzie, 1985 ; Olson *et al.*, 1984). This result has led to the

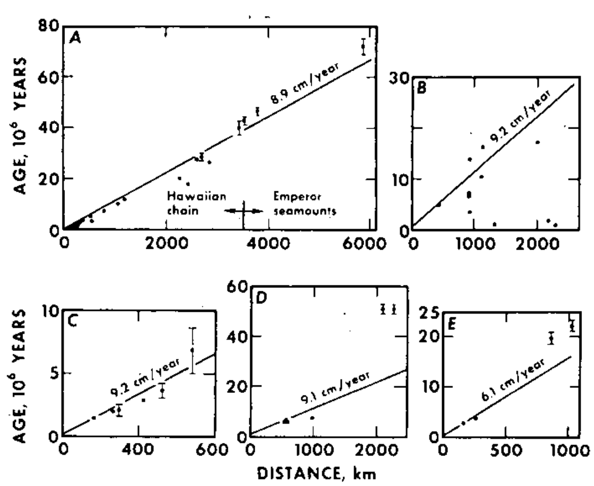

Figure 6. Pacific linear volcanic chains with active volcanoes at one end are shown as aging with distance along the chains. The fit with the rate of propagation for the chains predicted by Minster et al. (1974) is good and later work has improved it. The Cook-Austral islands are not readily attributable to a single hot spot.

A. Hawaii-Emperor chain.
B. Cook-Austral chain.
C. Marquesas chain.
D. Pitcairn-Tuamotu chain.
E. Kodiak-Bowie chain.

From Basaltic Volcanism Study Project (1981).

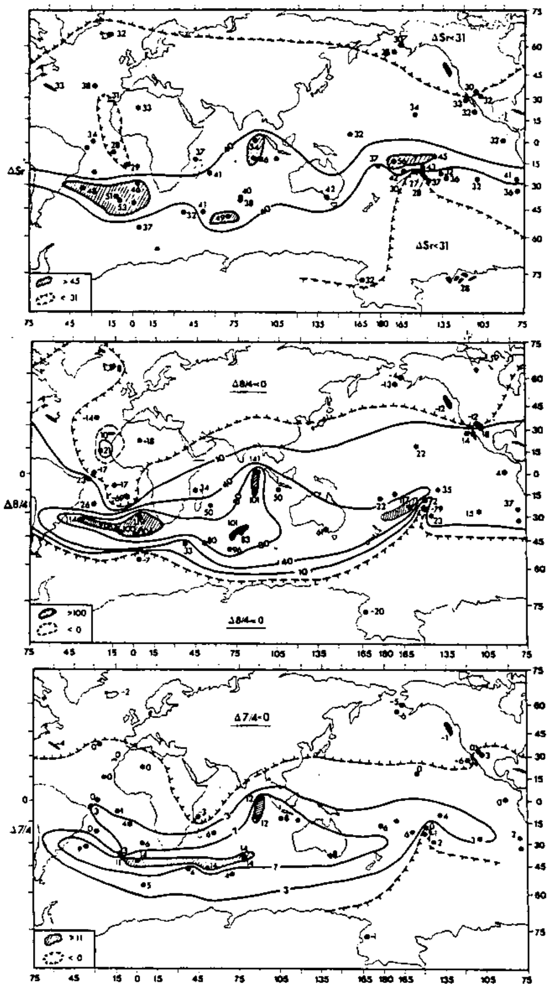

Figure 7. World maps (Miller cylindrical projection) showing distribution of the ΔSr (upper), Δ8/4 (middle) and Δ 7/4 (lower) anomaly criteria ; contours are fitted by eye and are subjective in many areas of non-existent data. Also shown on all three maps are data of the Ninetyeast Ridge, although these are samples of older age and should be plotted at a more southerly position, consistent with their location of origin. From Hart (1984).

development of mantle models where the upper mantle is a well-mixed, steady-state reservoir that is continuously replenished by entrainment of material from the lower mantle and depleted by extraction of continental crust (Galer and O'Nions, 1985). In this model, the mantle is analogous to a "layer cake" in that it is compositionally and kinematically stratified. Other workers view the mantle as a "marble cake" (Allègre and Turcotte, 1985), in which the heterogeneities introduced into the mantle by subduction, such as the oceanic crust and lithosphere, are drawn out into very thin sheets.

Understanding the balance between isolated reservoirs and convective stirring requires abundant observational data on the organization of heterogeneities. For example, the significance of the Dupal anomaly (Fig. 7) is not yet understood even in an observational sense. It is not clear whether it is confined to large plumes, or encompasses small seamounts, or extends to the MORB compositions from the region, or how it has evolved with time. Is this a region of hemispheric size that has been in convective isolation for two billion years or not ? On the smallest scale, it is not known whether short wavelength heterogeneities are in fact ubiquitous, as would be predicted from some models of convection, or whether their occurrence is restricted to certain regions.

Some of the most useful information could come from determining the longevity of the geochemical signature of each hot spot. If some hot spots have a unique and persistent chemical signature, and rapid convection in the upper mantle effectively disseminates heterogeneities and mixes different components, then this would imply convective isolation of the hot spot source. We know that many hotspots have a distinctive isotopic chemistry as is shown in Figure 9, but do the narrow clusters of values that characterize each hotspot shift with time ? If the chemistry of each hotspot were to shift radically with time, it would seem likely that the mantle is made of "blobs" and that a hotspot taps each blob one at a time. If the chemistry were to remain the same (perhaps with occasional excursions away from and then back to its average composition) for the lifetime of a hotspot, however, this would imply a large uniform reservoir that has not been thoroughly mixed with other parts of the mantle. Such tests of temporal variability are particularly important for the isotopic "end members" such as St. Helena and Kerguelen.

Geochemical mapping of the oceanic crust, including intraplate volcanism, is the next best option to the (obviously impossible) direct observation of the three-dimensional chemical mantle structure. If exemplary regions of the oceanic crust are mapped geochemically in sufficient detail, then there will be a firm data base that models of convection will have to explain. With such a data base, it will be possible to address questions about the number and size of reservoirs that are convectively isolated in the mantle, and the convective regime that would be able to create and preserve the observed organization.

The discussion to this point has included trace element and isotopic geochemistry only as a fingerprint of mantle domains, with indirect connection to the variations in major element composition and temperature that would actually be driving the convective processes. There is now gradually emerging, however, the possibility of using major element variations in the crust and in ultramafics to make inferences about the temperature of the mantle from which the crust formed (*e.g.* Dick *et al.*, 1984 ; Klein and Langmuir, 1987) and, with less certainty, to infer variations in the major element composition of the mantle source as well. The combination of the major element with the trace element and isotopic data should provide an additional dimension to the relationships to be discovered between the geochemistry and geophysics of the mantle.

Implications for Geochemical Cycles and Mass Balances

The combination of data on the volumes of mantle reservoirs with their chemical composition that would ultimately result from a large geochemical mapping program would provide new constraints on understanding the fluxes of the global plate tectonic cycle and on fundamental questions of earth differentiation. It has been known for about two decades that ocean floor basalts are derived from a mantle region that is depleted in incompatible trace elements. When isotopic data for neodymium became available, it became possible to calculate the mass of this depleted reservoir by considering the mass balance between continental crust, depleted mantle and primitive mantle. The result was that the depleted region of the mantle constitutes about 30 to 50% of the total mantle. The question is of fundamental importance because it is reasonable and tempting to identify the depleted mantle region with the upper mantle above the 670 km seismic discontinuity. If this is correct, then that discontinuity is likely to be a compositional rather than a phase boundary, and mantle convection is likely to occur in two separate layers.

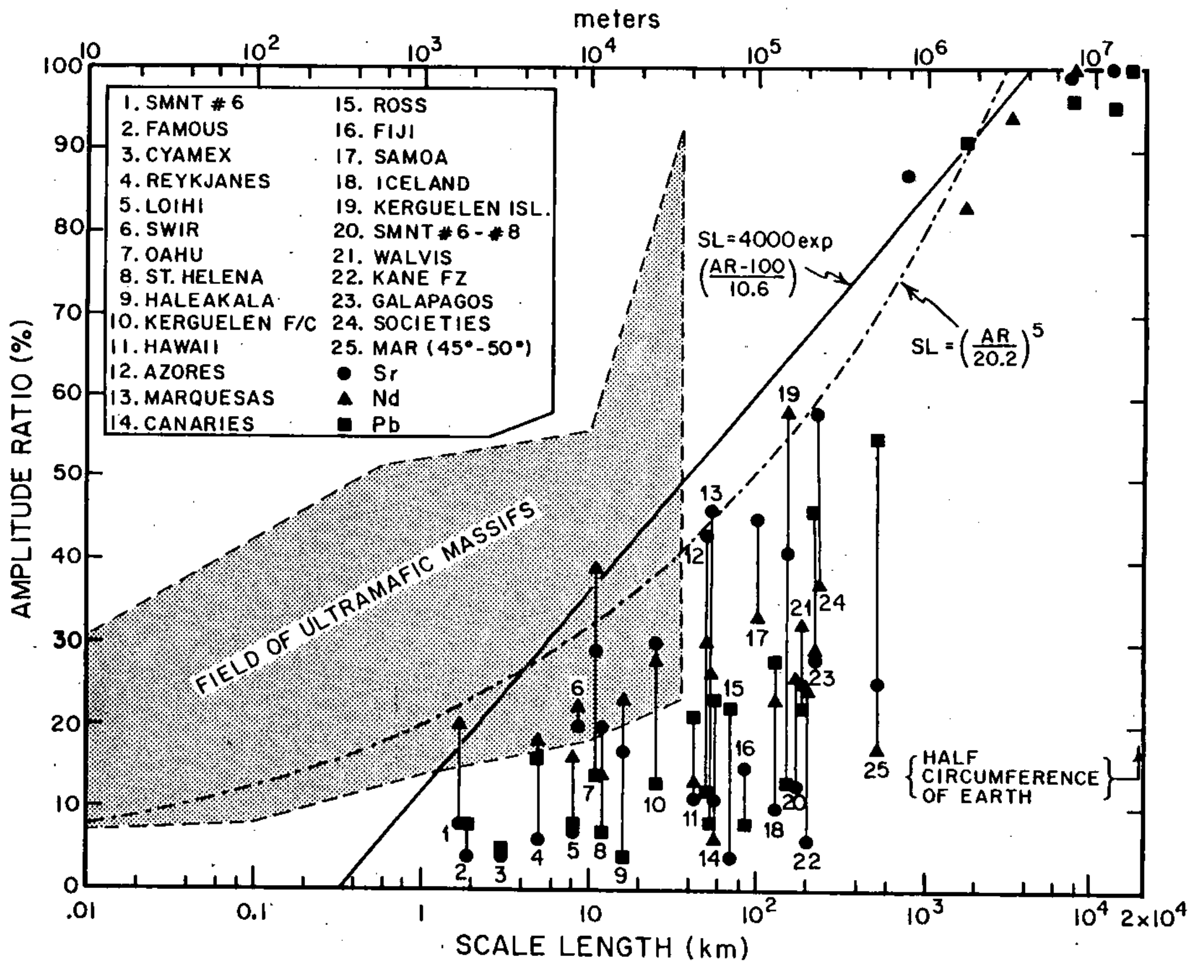

Figure 8. Amplitude ratio (*AR*) versus scale length (*SL*) for various volcanoes, islands, island groups, and ridge segments. Vertical lines connect the *AR* values observed for Sr, Nd, and Pb at each locality. Points for Sr, Nd, and Pb plotted at 100% *AR* are the normalizing values, given for Nd by Kane-Walvis (*SL* = 7780 km), for Sr by Kane Societies (*SL* = 12 400 km), and for Pb by mid-Indian Ocean ridge-Tubuai (16 700 km). Other points plotted in upper-right quadrant are for other various island pairs that provide large *AR* for minimal scale lengths (Nd : Walvis-mid-Atlantic ridge, 94%, 3030 km ; Sr : Tahaa-Juan de Fuca, 99%, 7100 km ; Tahaa-Tubuai, 87%, 770 km ; Pb : Walvis-Tubuai, 95%, 13 500 km ; St. Helena-mid-Indian Ocean ridge, 96%, 7600 km ; Walvis-St. Helena, 91%, 1700 km). Arbitrary exponential and power-law curves are shown as possible upper-bound fits to the data. Also shown is the outline of the field for ultramafic massifs. From Zindler and Hart (1986).

One serious difficulty with the above approach has been the assumption that the upper mantle consists entirely of such depleted material as is found in "normal" MORB from ocean ridges. Ocean island basalts have traditionally been omitted from this consideration because they were believed to be derived from the deeper, primitive reservoir and to be volumetrically insignificant. But there are potentially large volumes in the total of volcanic seamounts, oceanic plateaus, and other intraplate volcanic events that could affect this global mass balance.

It is also important to assess the volume as well as the isotopic composition of the various geochemical "components" that have been identified, since it is the volumes as well as the compositions that ultimately must be related to the ancient fluxes both within and into the mantle sources of the ocean crust.

Relationship to Geophysical Measurements

Since the understanding of mantle dynamics and mapping of convective flow in the mantle is a primary goal of our research, it is necesary to include geophysical monitoring with the geochemical sampling and data synthesis. A new perspective arises from the opportunity to correlate the results from seismic tomography and other geophysical methods such as satellite geodesy with geochemical data from the surface. The velocity heterogeneities revealed in seismic tomography, for example, are probably related to temperature variations and are likely to be directly related to mantle convection. Geochemical variations, although not directly related to the mechanisms which cause convection, are expected to be directly related to long-term mantle flow and mixing given the heterogeneities' relationship to surface tectonic features such as ocean islands, hot spot traces and ridge crest elevation. These considerations argue for the establishment of oceanic sea floor and sub-sea floor observations to improve our capacity for mapping mantle seismic heterogeneities as a complement to geochemical mapping. The resolution of seismic tomography will be significantly enhanced by deployment of instruments in drill holes. Thus the next decade holds the potential for a far more sophisticated integration of geophysical and geochemical data. Once the tomography affords sufficiently high spatial resolution, it should be possible to interpret the seismic velocity structure in terms of mantle rock compositions inferred from basalt chemistry.

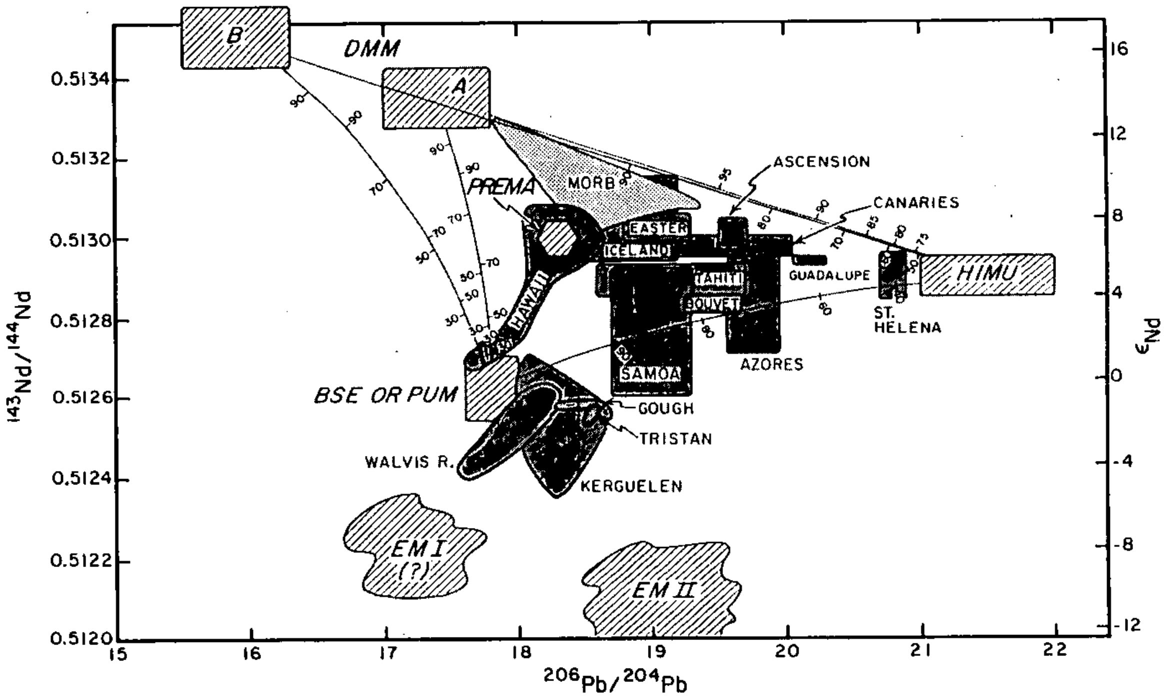

Figure 9. $^{143}Nd/^{144}Nd$ **vs.** $^{206}Pb/^{204}Pb$ **for ocean islands and MORB. Also shown are postulated isotopic compositions of mantle components. From Zindler and Hart (1986).**

In general, the relationship of geophysical to geochemical measurements holds great potential. For example, geophysical observations of the depth, heat flow and geoid anomalies over regions of active mid-plate volcanism show that the rising plume of source material for ocean island basalts can be associated with an energy flux that produces thermal anomalies of several hundred degrees in the oceanic upper mantle. The energy flux should be closely coupled with petrologic and geochemical consequences. Drilling the flexural moat of a hot spot chain can test the models of thermal and viscosity structure beneath hot spots, which then would relate to models of basalt generation. The important point is the growing recognition that various geochemical and geophysical methods provide constraints that are closely linked, and need to be considered together.

Mantle Kinematics and Dynamics

Hot Spot Traces and Mantle Drift Rates

Precise dating of basalts from the islands and seamounts of the Hawaiian-Emperor chain provided a conclusive test of the hot spot hypothesis, at least in the sense that it demonstrated the remarkable stability of this hot spot with respect to Pacific plate motion. Dates from other island/seamount chains in the Pacific permit testing the hypothesis that the hot spots are perfectly fixed in the mantle, and that the Pacific plate is perfectly rigid, and thus all hot spot track ages can be fit with a chosen motion of the plate over the hot spots. To first order this hypothesis fits the data quite well (Fig. 6). To second order, the fit is not exact - each hot spot has a "drift" through the mantle, or the plate is distorting. The hot spots appear to drift on the order of 5-10 mm/year, or almost 10% of the Pacific plate velocity, and about as fast as slow spreading plates. Unfortunately, no other chain has been dated as precisely as the Hawaiian chain and the departure from "fixity" has not been established definitively. For this purpose, it is necessary to date the main shield-building phase of volcanism (which on Hawaii lasts only about one million years), rather than the final gasps of volcanic activity that may continue for several millions of years. It is preferable to use seamount chains rather than aseismic ridges for this test to avoid the unknowns of hot spot/rise crest interactions. The seamount chains need not be on the same plate if accurate reconstructions from magnetic anomalies are available.

If the "drift" of each hot spot with respect to a fixed frame could be measured, this would give important information on the nature of deep mantle flow. Suppose for example that the "motion" of all hot spots was found to be away from regions of subduction zones and toward areas of upwelling, or showed some other regular pattern. This might directly reveal the horizontal flow of the lower mantle carrying the hot spot conduits along in its return flow. Clearly this would be a pivotal constraint on modelling convection in the mantle. Precise dating of seamount chains is needed to determine if there is an organized pattern of hot spot motions.

Interaction of Hot Spots with Ridge Volcanism

When an oceanic ridge is located near a hot spot, some of the hot spot material may be channeled sideways toward the ridge crest. Evidence for this has been found on the southern mid-Atlantic ridge (*e.g.* Hanan *et al.*, 1986). If material from off-axis plumes is indeed funneled toward the MAR, this will have profound implications for the possible modes of upper mantle flow, and the way in which "plume" reservoirs interact with MORB reservoirs. For example, rapid mixing due to small scale upper-mantle convection or in large and permanent magma chambers might not be consistent with this observation. In regions such as these, drilling should be able to reveal the detailed mantle kinematics.

Hot Spots versus Hot Lines

The relative stability, longevity (~70 Ma for the Hawaiian-Emperor chain), large volume of magma (> 109 km^3), and the large lithospheric bulges associated with the larger hot spots have led to widespread (though not unanimous) acceptance of Morgan's plume theory for the origin of hot spots. Accordingly, plume convection would constitute one of the two most important modes of mantle convection (the other one being the broad mantle upwelling at ridge crests and subduction of lithosphere at consuming plate margins).

There is, however, another form of large-scale, off-ridge volcanism, that which produces linear "aseismic" ridges, the so-called hot lines. These features are chemically and isotopically more similar to ordinary ocean island basalts than to MORB. Such hot lines have been interpreted as evidence that the source of the magmas is located in the asthenosphere, which is tapped by some sort of lithospheric fracture, rather than in a deep-mantle plume. A critical test of the hot-line interpretation would be to date the ages of initiation of volcanism along the line. If this reveals a Hawaiian-like age progression, the hot line would represent a hot spot with continuing activity. If volcanism occurred simultaneously all along the line, the hot line would represent a phenomenon that is fundamentally different from hot spots.

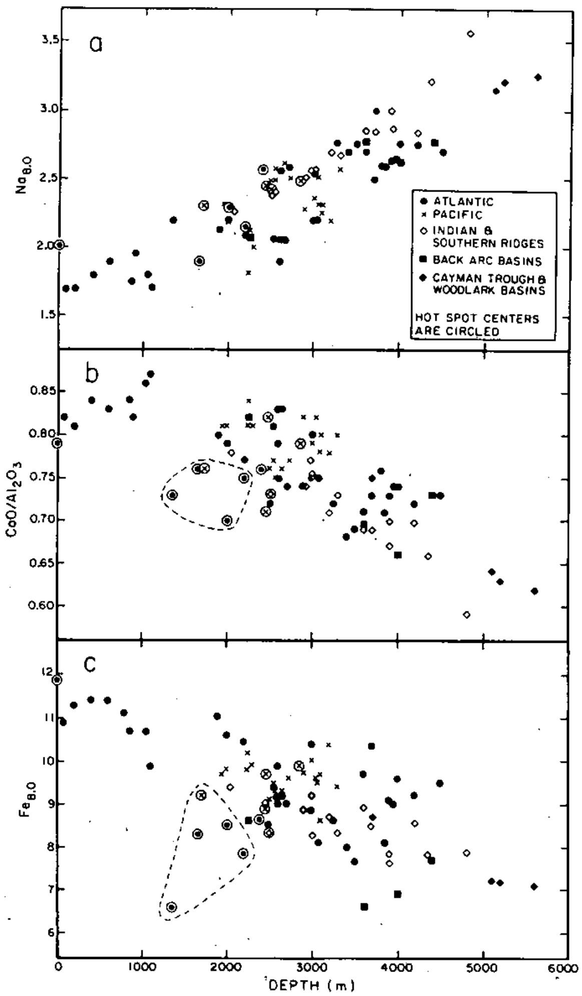

Figure 10. Regional averages of axial depth versus (*a*) $Na_{8.0}$, (*b*) CaO/Al_2O_3, and (*c*) $Fe_{8.0}$ for samples from the mid-Atlantic ridge (solid circles), Pacific ridges (crosses), Indian and southern ridges (open diamonds), back-arc basins (solid squares), and the mid-Cayman rise and Woodlark basin (solid diamonds) ; recognized axial hot spot centers are circled. Data points from the Azores, Jan Mayen and Galapagos hot spot centers are enclosed in a dashed field. $Na_{8.0} = Na_2O + 0.373*(MgO) - 2.98$; $Fe_{8.0} = FeO + 1.664*(MgO) - 13.313$. $Na_{8.0}$ and $Fe_{8.0}$ are calculated for samples with 5.0-8.5 wt % MgO ; CaO/Al_2O_3 are calculated for samples with >5.0 wt % MgO. From Klein and Langmuir (1987).

Dynamics of Ascent and Decompression Melting in a Rising Mantle Diapir

Intraplate volcanoes may display distinct cycles of depth and degree of partial melting through their life span that witness the dynamics of ascent and melting in a rising mantle diapir. These chemical cycles may be revealed, in particular for the early stages of volcanism, by drilling young hot spot volcanoes and the submerged portions of islands/seamounts that are not accessible to study on land.

Drilling Strategy

The very concept of mapping the crust geochemically to investigate mantle composition and dynamics entails a large number of drill holes, as is clear from the diversity of drilling targets both in terms of crustal type (seamounts, plateaus, hot spots, hot lines, old crust, etc.) and especially in terms of the regional coverage that "mapping" implies. This concept can come to full fruition only if it is possible to drill shallow basement holes rapidly, so that over the course of the next decade there can be a large number of holes contributing to the geochemical mapping program. Design of the optimal plan for drilling will need to draw on both geochemical and geophysical expertise, and might be optimally accomplished with a long-term plan of investigation, rather than isolated goals in separated areas that are not coordinated with one another.

Although most of the holes can have shallow (<50 meters) basement penetration, there is the need for some deeper holes. In the case of oceanic plateaus and seamounts, for example, the representativeness of the uppermost few meters of basalt is not clear, and exploration of these features with holes of substantial penetration would be desirable. To understand the products of a seamount, and from them to understand the seamount's petrologic and geochemical evolution and its significance, it is necessary also to understand the volcanologic anatomy of seamounts. In this context, the Hawaiian drill hole being considered by DOSECC is of fundamental importance since it would provide deep penetration of a very large "seamount" that could be compared to oceanic drilling of smaller edifices.

CREATION OF OCEAN CRUST AT SPREADING CENTERS

Since COSOD I the concept of ocean ridges has developed from a generic conception of ridges in general to an increasingly detailed and sophisticated description of their variability on all scales. Whereas it has long been known that ocean crust forms in response to decompression melting of the mantle beneath spreading centers, it is now increasingly recognized that thermal variations in the mantle over distances of several hundred kilometers lead to systematic variability in the bulk composition of the crust (Klein and Langmuir, 1987) and associated ultramafics (Dick *et al.*, 1984 ; Michael and Bonatti, 1985) (Figs. 10-11) as well as in crustal thickness. This variation, in addition to the obvious spreading rate variations, needs to be included in the consideration of the global variability of crust formation processes.

Over shorter length scales, there has been a watershed of new ideas concerning the processes that control the accretion of oceanic crust and lithosphere at mid-ocean ridges (*e.g.* Schouten and Klitgord, 1983 ; Fox and Gallo, 1984 ; Francheteau and Ballard, 1983 ; Macdonald *et al.*, 1984 ; Lonsdale, 1983 ; Christie and Sinton, 1981 ; Langmuir *et al.*, 1986 ; Detrick *et al.*, 1987). While there has been a good deal of healthy controversy and debate, most of the ideas have a common theme: along-strike and temporal variations in tectonic and magmatic activity are at least as important as the well-documented variations in structure perpendicular to strike (*i.e.*, aging of the lithosphere). A critical factor leading to the

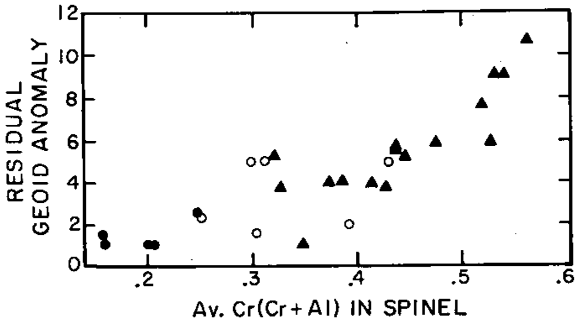

Figure 11. Cr/(Cr + Al) of spinel in dredged peridotites from the Atlantic and Indian Oceans versus the height of a residual geoid in meters. Modified from Dick et al. (1984).

new ideas is the technology to produce high resolution, continuous coverage maps and images of sea floor structures (*e.g.* SeaBeam, SeaMARC I-IV, Argo-Jason), the improvement of multi-channel seismic experiments, and more closely spaced rock sampling. Before the burst of new data brought about by these techniques, it was difficult to address questions relating to along-axis variations, and generic drilling of ocean crust seemed suitable. Now the detailed context of the drill site is an essential component of any drilling plan.

A major question concerning the crust formation processes at ocean ridges is how the basic conceptual components of the magmatic system relate to the new detailed observations of variability along strike. The four basic components of crust generation are (1) the production and segregation of melt in the (possibly heterogeneous) upper mantle ; (2) the ascent of this melt to crustal depths ; (3) the temporary storage of the magma in crustal reservoirs ; and (4) the conversion of the magma through eruption and crystallization into normal ocean crust. Some critical questions concerning these basic components that relate to along-strike variability are : What is the horizontal and vertical extent of the zone of melt production in the upper mantle, and how does the extent of melting vary spatially and through time ? To what extent is magma focussed towards discrete injection zones into the crust ? Over what time and space scales are crustal magma reservoirs supplied ? What are the characteristic time and length scales of ridge crest magmatism ? How do the basic components of magma genesis respond to changes in spreading rate and the regional thermal environment of the mantle ? A challenge for ridge crest studies is to relate these general questions to the new detailed descriptions of the nature of ridge crest segmentation.

Ridge Crest Segmentation

An important development in conceptions of ridge crest segmentation is the recognition of different types of ridge offsets along spreading center axes that correlate well with along-axis depth variations (Macdonald *et al.*, 1984 ; Francheteau and Ballard, 1983) and appear to have significance for the processes by which the crust is formed. Along strike there appears to be a variation in crustal stratigraphy and structure with a pronounced thinning in the vicinity of fracture zones (*e.g.* Detrick and Purdy, 1980). The abundance of altered residual mantle peridotite and basalt relative to gabbroic rocks dredged at some fracture zones also suggests that layer 3 is attenuated or locally absent in their vicinity.

The reason for the variations in crustal thickness and structure along ocean ridges is an area of controversy. Some proposed that crustal thinning immediately adjacent to the transform was caused by the juxtaposition of the old, cold lithosphere against hot, young asthenosphere at a ridge-transform intersection (*e.g.* Fox and Gallo, 1984). It was reasoned that this would inhibit melting and melt segregation in the underlying mantle, resulting in the formation of thinner ocean crust and lower extents of melting near large offset transform faults. Although this postulated "transform edge effect" may be real in some cases, it is evidently not a sufficient explanation. Petrologic and multi-channel seismic data from very small offsets show similar effects to those previously observed at large offset transform faults (*e.g.* Mutter *et al.*, 1984 ; Langmuir *et al.*, 1986). Thus "edge effects" similar to those first associated with transform faults can be observed even where there is no transform or tectonic cold edge. It is not yet known if the crust actually thins across small offsets of the spreading center axis such as overlapping spreading centers. The new data show that aspects of the edge effects must be associated with the magmatic cycles at ocean ridges, as was originally proposed for propagating rifts (Christie and Sinton, 1981), and can be to a certain extent decoupled from tectonic offsets.

A major question about magmatic segmentation along ridges concerns the scale of segmentation and how it relates to along-axis bathymetry and the mechanisms of supply of magma from the mantle. It is not yet clear what the relative importance of different size offsets is. One model (Whitehead *et al.*, 1984 ; Schouten *et al.*, 1985) suggests that ridge volcanism is another example of segmented volcanism like that in island-arcs. The proponents suggest that transforms and other major ridge axis discontinuities define regularly spaced accretionary cells or magmatic centers with thinner crust generated between them. They point to the scarcity of gabbroic rocks in transforms, noted earlier, as indicating that magma chambers rarely exist between spreading center segments. In this model, flow of melt from the mantle is concentrated at regularly spaced points beneath the midpoints of individual spreading center segments by some form of gravitational instability in a partially molten layer in the upwelling asthenosphere (Fig. 12). This produces a series of shield volcanoes, elongate parallel to the ridge axis and kept low by continuous extension of the crust.

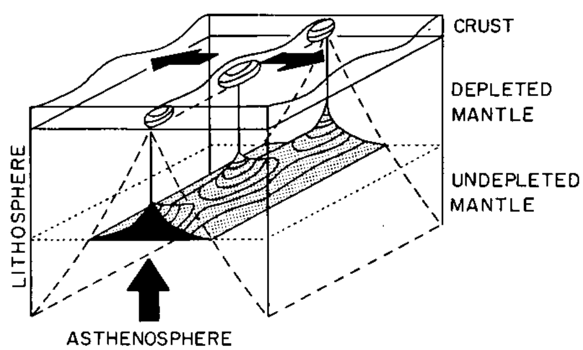

Figure 12. Viscous asthenosphere rises two-dimensionally beneath the boundary between two spreading lithospheric plates. The lithosphere thickens away from the spreading boundary (dashed lines). Above a certain level (dotted lines), the rising asthenosphere passes through a zone in which partial melt can form which collects at some level below the base of the lithosphere. Due to its lower viscosity and density, the partial-melt zone develops a gravitational instability leading to regularly spaced concentrations of melt which rise to the surface to form crustal magma chambers. The asthenosphere, effectively depleted by this process, must continue to rise viscously and on cooling become lithosphere. The wavelength of the gravitational instability (and the subsequent spacing of spreading centres or transform zones) should also depend on the width of the partial melt zone which is expected to be proportional to the spreading rate. From Whitehead et al. (1984).

The crust between magmatic centers is largely formed by lateral melt injection down the fissure system leading to thinner crust between magmatic centers.

An alternative view is that magma transport from the mantle into the crust is dominated by vertical porous flow. A porous flow, distributed injection model could have some focusing of magma due to the flow pattern and stress regime in the mantle, but would be likely to lead to a more dispersed input of magma into the crust. The principle difference between these models is the degree to which the flow of melt is focused to the midpoint of an ocean ridge. In both cases porous flow is the principal means of transport through the mantle. In the Rayleigh-Taylor instability model, however, the proponents (*e.g.* Schouten *et al.*, 1985 ; Thompson *et al.*, 1985) call for a much greater degree of lateral transport of the melt to centrally located instabilities feeding a principal magmatic center located near the midpoint of a ridge segment. In the latter case, the proponents (*e.g.* Christie and Sinton, 1981 ; Perfit *et al.*, 1983 ; Langmuir *et al.*, 1986) call for less focusing, and more local derivation of magmas from the mantle immediately underlying any point along the length of a ridge segment. The dispersion model predicts more variations in magma chemistry, reflecting changes in extent of mantle melting and composition along an individual ridge segment. The instability model predicts that the majority of magmas erupted along a ridge segment will have come from and have mixed at a central magmatic center, with longitudinal variability caused by processes in or just beneath the crust. In the latter case, the scale of lateral mantle heterogeneity that can be sampled by dredging rift axis basalts is largely limited to the segmentation length, while the former case suggests it is possible to sample variations in mantle composition and degree of melting by dredging basalts along a single ridge segment.

The key question that emerges from the new segmentation models for the ocean crust is : what is the scale of tectonic segmentation of spreading centers and how does such segmentation relate to melt production in the mantle and magmatic activity in the crust ? Addressing this question is not simply a matter of drilling or dredging or surveying, but requires a coordinated strategy of multi-disciplinary investigation.

A Strategy for Understanding the Genesis of Ocean Crust

While our understanding of ridge axis processes has evolved a great deal in the last few years, it has largely been based on a narrow ribbon of concentrated study restricted to the ridge axis. We now face the more difficult problem of extending the high resolution observations from this narrow, one-dimensional perspective, to a second dimension (broad areal coverage at high resolution on the flanks of ocean ridges), and a third dimension through deep drilling into the crust. One necessary step is to gain some sense of the persistence of the zero-age observations, by extending the high resolution observations, measurements and sampling to the flanks of both fast and slow spreading mid-ocean ridges over areas spanning several spreading cells. The cells chosen should include the full range of ridge-axis discontinuities, *i.e.* a major transform fault, a propagating rift and several smaller discontinuities such as OSCs and smaller ridge offsets.

Rapidly developing technologies of swath mapping, seismic profiling, and global positioning will soon provide an unparalleled capability for efficiently and accurately mapping and sampling features on and beneath the ocean floor. The high quality spatial resolution of these new mapping and sampling techniques allows strong inferences to be made about the evolution of features initially produced at spreading centers. All of these studies would document the segmentation and geophysical and geochemical organization of the ridge in question and would provide the context in which drilling should proceed.

Such studies cannot provide information, however, concerning the active processes, variable on a short time scale, which are involved in making crust. Basic questions about the kinematics and dynamics of ocean crust generation will never be adequately addressed by higher resolution mapping or continued exploration of the less well-known portions of the ocean basins. Answers to these questions require direct observation and documentation of the episodic processes that produce these features on the time scales of their formation. For example, monitoring of an active ridge could provide information on the location, size and duration of episodes of magmatic injection into the crust, and the gradual accumulation of this information would provide definitive evidence concerning some of the questions raised above concerning the relationship between magmatic and tectonic segmentation that can never be achieved by mapping and sampling.

The oceanographic and earth science communities are in a position scientifically and technologically to initiate programs leading to the installation of one or more permanently instrumented volcano observatory/laboratory complexes on submarine spreading centers. The goal of this natural laboratory approach would be to determine, and then model, the temporal and spatial covariation among the physical, chemical and biological processes involved in the generation and evolution of the oceanic crust/mantle system.

COSOD I identified as its first drilling priority the establishment of natural laboratories in active areas. As defined by the COSOD I Report the natural laboratory concept included : "arrays, or clusters of holes, some deep, some relatively shallow, grouped together in fours and fives, in particularly critical (active) parts of the ocean floor... They would be used for emplacement of sophisticated instruments, some during the drilling period, and others for long-term monitoring after drilling had ceased. Within each laboratory complex, one hole would be targeted for deep penetration to allow sampling material from hitherto unreached levels in the ocean crust."

An essential philosophical component of this approach was that of focused drilling efforts on important, well documented and carefully selected problems and sites. In the intervening years since COSOD I, very little of substance has been accomplished to implement this concept. During the same period, however, perceptions of what a natural laboratory could be have evolved beyond the drilling-oriented concept put forth in the COSOD I Report, and the priority now is to set up "natural laboratories" at spreading centers using methods other than drilling, and then to have drilling be integrated as one component of a broader natural laboratory program.

Ideally, selection of a small number of optimal laboratory sites would involve an exhaustive search for portions of the global rift system that are vigorously active volcanically, tectonically and hydrothermally. Integrated and concurrent time series measurements of magmatic and volcanic activity, strain rates, seismicity, hydrothermal output, biological productivity and watercolumn plume dynamics would allow quantitative definition of key lithospheric accretionary processes as well as the nature of the feedback mechanisms that link them. Sea floor and watercolumn mounted instrument arrays would substantially augment those originally envisioned during COSOD I as being situated in bore holes. Significant sections of a ridge crest segment would be an appropriate scale for this focused effort at documenting time-series change along spreading centers.

An example of one important focus for a ridge crest natural laboratory includes a concerted effort to define nature and dynamic evolution of the transient boundary between molten rock and fractured rock at the margin of a magma chamber. The physical and chemical properties of rocks and fluids under geologically realistic temperatures, pressures and strain rates involved at magma chamber boundaries are almost

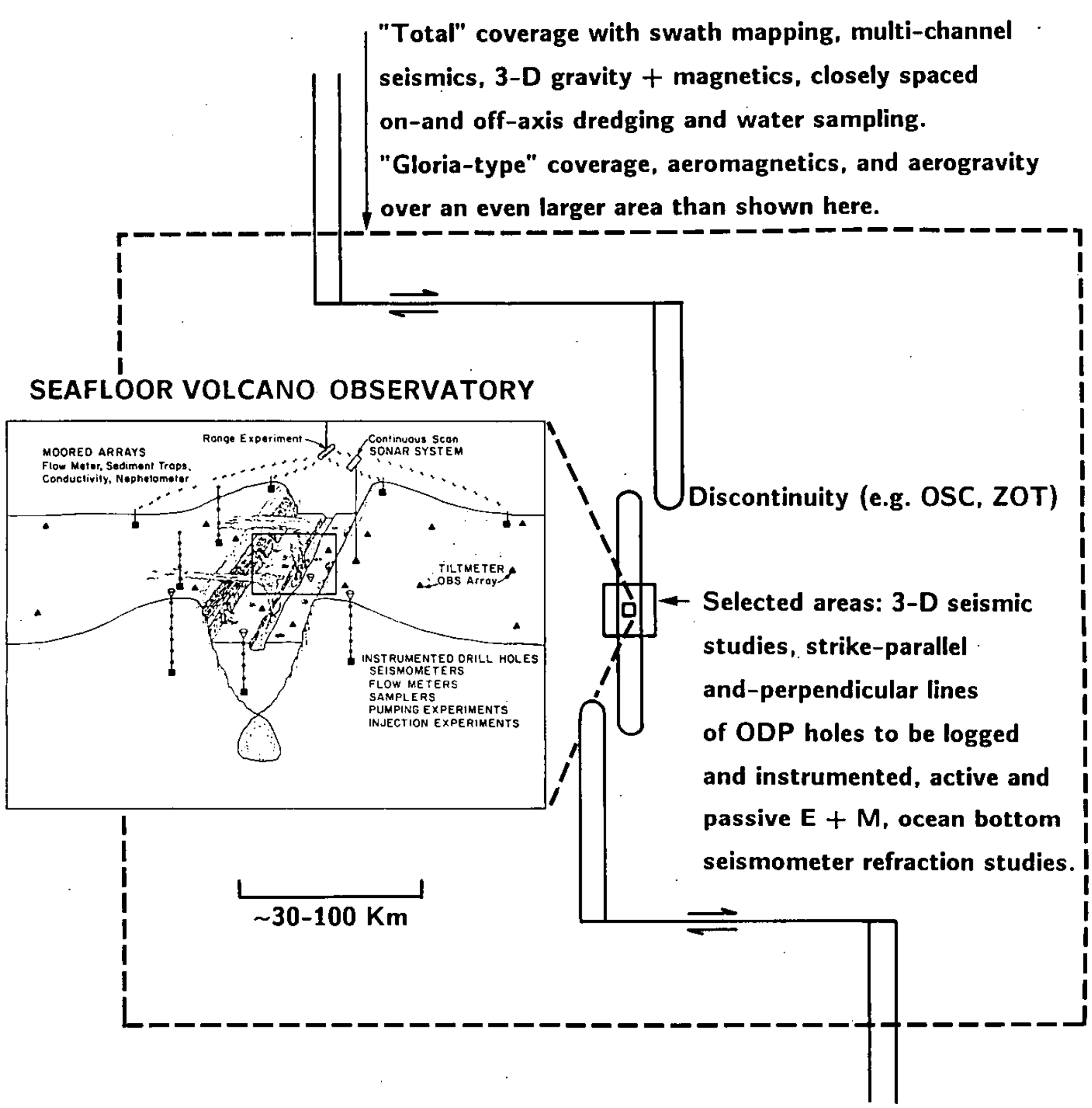

Figure 13. Strategy for the integrated study of accretionary processes in which strike-parallel and strike-perpendicular lines of logged and instrumented ODP holes are an essential component. As deeper and more closely spaced ODP holes are required by the questions we hope to answer, so is a greater effort in contextual geologic, geophysical, and tectonic studies over a much larger area than the locations of the drill holes. The few deep drill holes and larger number of shallow drill holes provide critical stratigraphic and geochemical tie points for other measurements which cover larger areas. Establishment of a sea floor volcano observatory might be attempted in this context.

completely unknown. Yet this is the boundary at which the solid oceanic crust is formed : the style and vigor of magmatic evolution within the chamber as well as the rate and intensity of fluid circulation in the enclosing hydrothermal system are intimately coupled to the rates of heat and mass transport across this transient interface. Deep ocean drilling and the natural laboratory approach are uniquely suited to study this crucial but ephemeral feature of crust-mantle evolution.

An important additional piece of information concerning the general problems of crust formation and ridge segmentation will be the crustal stratigraphy as determined by drilling. Drilling is needed to sample the net volcanic and hydrothermal results of ridge crest volcanic activity, the bulk composition of eruptives, the relative crystallinity and morphology of lava flows, flow thicknesses and chemical stratigraphy, the net hydrothermal alteration and how these may vary with respect to tectonically defined position within a spreading cell. Although it would be ideal to have the stratigraphy in the natural laboratory environment, in terms of drilling capability the least likely area to have success with deep penetration is young, hot and fragmented volcanic terrain on a fast spreading ridge. Results from Leg 54 demonstrated the far greater difficulty of drilling on young crust at the East Pacific Rise than at the mid-Atlantic ridge. Thus the drilling aims that require deeper penetration on fast-spreading ridges may need to be carried out on older crust.

It is clear that while ocean drilling is a key element in any program designed to understand the physical, chemical and biological consequences of mass and energy transfer within the global ridge system through time and space, it cannot proceed in isolation (Fig. 13). A balanced, four-pronged approach to the study of ocean crustal formation should include : 1) an

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extensive program of mapping and sampling the ridge crest and related environments to develop an accurate two-dimensional picture of the structural and chemical components in the system ; 2) focused drilling efforts on carefully selected, broadly representative portions of well-documented ridge crest with the goal of helping to characterize an active volcanic system ; 3) use of sea floor, bore hole, and watercolumn mounted instrument arrays to obtain a wide variety of coordinated and synchronized time series measurements of the interrelated igneous, deformational, hydrothermal and biological processes operating on a decadal time scale ; 4) deep drill holes on well-characterized older crust to obtain complete lava stratigraphy and the net effects of hydrothermal processes. This approach is designed with the recognition that deep penetration with good recovery is an order of magnitude more difficult on hot, active, fragmented volcanic crust than it is on older, cooler, altered crust, but that some shallower drill holes will be necessary in the active volcanic regime.

Ideally, there should be in the long run a carefully selected suite of shallow and deep drill holes that span several spreading cells at a range of spreading rates. The array of shallow holes should include a line of holes along strike in young lithosphere. Several such lines should be drilled at key isochrons along strike, and there should be at least two cross-strike lines, one near the elevated mid-section of the spreading cells, and one near the termination of the cells at ridge axis discontinuities. Provided the control with respect to various types of offsets can be determined well by the extensive site surveys, it is not necessary that this drilling occur in very young crust. In fact, optimal sites might be on older crust, particularly in the Atlantic, where multi-channel seismic studies can give good structural control only on older crust. Drilling should occur at different ridge discontinuities, including small and large offset fracture zones. At the latter, the non-transform wall, where several photogeologic and SeaBeam surveys have shown large areas of uplifted volcanic crust, should permit drilling of the fracture zone crust undisrupted by transform tectonics, permitting determination of the degree to which crustal structure is attenuated at different spreading rates.

Ultimately, assessment of magmatic processes requires long continuous cores of plutonic rocks of known orientation which are not provided by rock dredging. Hence a major goal of ultra-deep drilling in the ocean crust is to obtain a continuous section of the deep plutonic layers and shallow mantle to assess the processes by which melt is generated and transported from the mantle and the physical and chemical processes by which it is transformed into crust. Given the pronounced segmentation of the ocean ridges and the fact that the rate of magma supply must vary 30-fold to account for the relatively uniform thickness of the ocean crust and the large range of spreading rates (6-180 mm/yr), these processes, and the size and longevity of magma chambers, must vary considerably at different ridges and in space and time. It is unlikely that deep drilling, given the cost and time involved, will ever be sufficient to resolve all these variations.

Studies of transforms have shown that large and massive exposures of plutonic rocks are exposed along their walls and floors. To a lesser degree such exposures appear to exist in the rift mountains and valley walls of slow spreading ridges. Careful bathymetric, dredging, photogeologic and submersible surveys then could locate selected deep sections of tectonically exposed crust from which drilling could provide long continuous cores to complement the holes drilled into layer 2 and the rare ultra-deep holes.

The time scale on which the thorough mapping and sampling could be done properly, and on which the preliminary experiments could establish the appropriateness of any site for concentrated drilling, may be on the order of five to eight years. One could argue that selection of natural laboratory drill sites be delayed until the technology for such efforts is available and sufficient information is at hand to make wise choices. On the other hand, it may be necessary to progressively develop the capability of drilling in the zero-age environment and of deploying instruments in drill holes, and from this perspective early efforts in settings that might not yet be known to be optimal would be necessary for the eventual accomplishment of the scientific objectives.

CRUST/MANTLE INTERACTIONS AT CONVERGENT PLATE MARGINS

Fluxes at convergent plate margins include many more processes and distinctive components than those at spreading centers (Fig. 14), and many critical processes that ultimately control the fluxes, such as deep dehydration reactions in the down-going plate, are not possible to study directly, and in many cases are even difficult to study experimentally. Whereas a total crustal section of old oceanic crust immediately gives an unshakable data point concerning a product of sea floor spreading and the raw input for convergent margins, we can envision no such definitive data for net fluxes at a convergent margin. Despite the difficulties, convergent margin fluxes are so central to solid earth geochemical cycles that they demand study : the distillation of the continental mass from the mantle that may occur at convergent plate margins is one of the most fundamental aspects of terrestrial differentiation. And the potential for the creation of mantle heterogeneities at convergent margins is unparalleled as the mantle wedge is invaded by materials from the subducted slab as it is metamorphosed, dehydrated, and perhaps melted, and as the residual products of such reactions are recycled into the mantle.

There are two major aspects of fluxes at convergent margins that are accessible to study and require drilling as one of the means of study : raw input from the down-going plate, and crustal output into the over-riding plate. Neither of these two first order pieces of information for evaluating fluxes at convergent margins are well known. In fact, there is not a single hole on a down-going plate outboard of an arc that penetrates significantly into the zone of upper crustal hydrothermal alteration of the igneous basement !

Crustal Output to the Over-Riding Plate

A total inventory of the diverse magmatism above subduction zones over a specific time period yields the output flux for this environment. Study of crustal outputs obviously begins on land - where most study has been concentrated - but land-based studies can only partially address the problem. The subaerial portions of an intra-oceanic arc represent a tiny fraction of the present day magmatic budget at a convergent plate margin. In some arcs less than 50% of the edifices are subaerial, and of these perhaps only 20% are accessible.

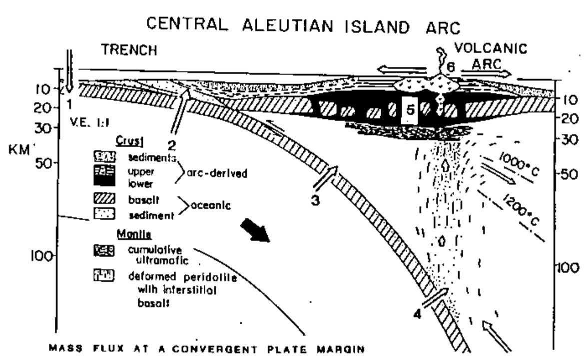

Figure 14. Some potential fluxes and processes that may operate at a typical convergent margin.

Surface exposures also tend to provide a highly inadequate record of early magmatism in any particular arc.

There are two ways to obtain a more complete and representative record of arc output through drilling. Drilling in the over-riding plate is essential to complete the available record from surface exposures in volcanic arcs and from dredge hauls on scarp slopes in both island arc and back-arc regions. Such drilling can also explore the arc basement, and hence obtain information concerning the characteristics of its earlier history and how it may have evolved through time. It is also noteworthy that the case to reject ophiolite sequences as typical of the ocean crust largely reflects suggestions that many were formed at or near a convergent margin. Thus deep drilling in the over-riding plate is further identified as a test of models for ophiolite generation.

An even more promising approach lies in the sediments of oceanic regions adjacent to arcs, where there should lie the intact record of the arc's evolution. Clastic aprons in back-arc areas, together with forearc basin deposits, offer an excellent opportunity to obtain a continuous and undisturbed record of subduction-related magmatism. Moreover, recovering a complete section of at least the thinner of these deposits requires fewer technological advances in sample recovery than drilling in the poorly consolidated sands of proximal deposits. Clastic aprons can record magmatic activity over the last 25 Ma, and thus they can provide information on present-day output fluxes, which should arguably be averaged over a 2-5 Ma time span, and on the links between tectonics and magmatism on a regional scale. Most observers regard magmatism as episodic, and there is some suggestion of a 10 Ma period of relatively little magmatism between 25-15 Ma in circum-Pacific arcs (Kennett *et al.*, 1977). Drilling in selected clastic aprons would test that suggestion and provide an exciting new data base with which to evaluate the local causes of magma generation and of magmatic periodicity. Drilling is perhaps the only way magmatic fluxes can be charted back in time. It is also important to note that the oceanic plate contains crustal components from the arc that appear to be recycled into the mantle at the arc. Thus drilling on the over-riding plate also contributes in some sense to the input side of the convergent margin problem.

An additional important component of arc output in intra-oceanic convergent margins are the back-arc spreading centres, which constitute a significant portion of the total mass flux from the mantle at some convergent margins. Even in continental areas the equivalent regime may be a site of material brought into the over-riding lithosphere. Chemical constraints suggest that back-arc basins tap a mantle source with striking similarities to the source of ocean ridge basalts (*e.g.* Hawkins, 1977). Back-arc basalts also contain, however, a significant, although variable "arc component" which present models derive from the down-going slab (*e.g.* Hawkins and Melchior, 1985). A proper understanding of the nature and origins of such subduction components in both arc and back-arc magmas requires much clearer documentation of the interaction between such magma types both spatially, and with time in the development of an arc-back-arc system.

Input to the Subduction Zone

In the 0-200 my transit of the ocean crust across the earth's surface, pre-existing continental crust is added to the oceanic column as sediment and as hydrothermal alteration by seawater. The fate of this crustal material at the subduction zones is a key unanswered question in studies of global geochemical fluxes. At successively greater depths it can be scraped off, sweated out, melted out as a recycled component added to new continental crust, or returned to the mantle (see Figure 14). That the subduction process might have profound effects on the chemical evolution of both the continental crust and mantle was first recognized by Armstrong (1968). Since then there have been periodic appeals to convergent margin processes to explain the geochemistry of the mantle (*e.g.* Hofmann and White, 1982 ; Dupré and Allègre, 1983 ; Weaver *et al.*, 1986), but it is not yet clear that the convergent margin fluxes are in fact responsible for all the effects they are called upon to account for.

In some arcs there is now clear isotopic evidence for a contribution from sediments to arc magmas. This evidence resides principally in the Pb isotopes (*e.g.* White and Dupré, 1986 ; Fig. 15), and in recent data from the cosmogenic radionuclide ^{10}Be (Tera *et al.*, 1986). Data from Sr and Nd isotopes are more ambiguous because of virtually complete overlap between volcanics from convergent margins and from the ocean basins. Although there is isotopic evidence for some sediment contribution at some arcs, this contribution can still be argued only in the most general terms. One of the long-standing enigmas of arc volcanic chemistry concerns the very different ratios of incompatible trace elements that are observed there. As a general observation, there is much more homogeneity in these ratios in some arcs than there is likely to be in the lithologically diverse subducting sediments. If the source of these characteristic trace elements lies in the sediments, as it plausibly may, then the interelement ratios should to some extent reflect those in the specific mixture of sediments being subducted, and this mixture should vary from arc to arc. It may be that sediment mixtures are much more homogeneous than the end members of which they consist. But as of yet there is not a sufficient data base outboard of different arcs to address this question definitively.

The effect on the neighboring arc is only one aspect of the recycling problem at convergent margins ; another aspect concerns the creation of mantle heterogeneities that are later revealed at ocean ridges and in intraplate settings. The composition of subducted oceanic crust, with or without its sedimentary veneer, should differ in a number of ways from ordinary mantle, in part because of the effects of magma genesis at ocean ridges, in part because of the reaction with seawater, and in part because of the presence of sediment. These compositional differences can provide the basis for testing the recycling hypothesis : any mantle reservoir alleged to contain recycled oceanic crust should share the compositional characteristics of oceanic crust. The evidence that mantle plumes and oceanic island magmas contain a recycled component is, however, contradictory. The high $^{206}Pb/^{204}Pb$ ratios of some ocean islands would seem to be consistent with the recirculation of subducted crust with very high U/Pb resulting from hydrothermal alteration of the ocean crust. But

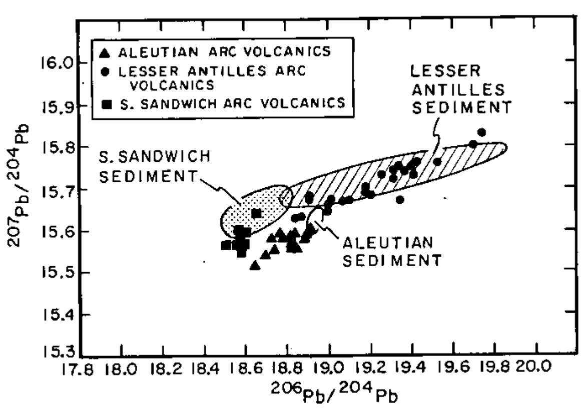

Figure 15. Pb isotopic compositions of three selected island arcs compared with Pb isotope ratios of sediment potentially being subducted beneath those arcs. Note the general correspondence between the isotopic characteristics of the sediments and the neighboring arc. From White (1987).

this argument may not be consistent with Th/U ratios (Hart and Staudigel, 1987). Pb/Ce ratios in all oceanic basalts are quite constant, and distinct from the ratio of continents and continent-derived sediments (Fig. 16) (Hofmann *et al.*, 1986; White, 1987). The uniformity of Pb/Ce ratios, together with the high concentrations of Pb in sediment and low Pb concentrations in the mantle, appear to be a strong constraint on sedimentary recycling. But Pb is abundant in hydrothermal effluents at ocean ridges and Ce is not, which may lead to low Pb/Ce ratios in deeper portions of the altered ocean crust. In this case the Pb/Ce ratio of the slab might balance the Pb/Ce ratio of the sediments, removing the objection based on Pb/Ce to mantle recycling. The major point of both these examples is that geochemical inferences concerning the importance of plate recirculation require detailed information concerning the compositions of the down-going ocean crust. In many cases, we know only the direction of the chemical effects associated with these processes (*e.g.* decrease in Pb concentration, increase in U concentration). We do not in general know the magnitude of the effects. In other cases, low temperature and high temperature alteration produce opposing effects (*e.g.* for the alkalis) and we cannot even be sure of the direction of net change (*e.g.* Hart and Staudigel, 1982).

A proper evaluation of the chemistry of the down-going plate, therefore, is central to any estimates of present input rates. Sampling of the oceanic section by drilling, including penetration to the limit of hydrothermal alteration, has not yet been accomplished for any oceanic crust adjacent to an arc. The crustal mass balance of many critical trace elements (*e.g.* U, Th, Pb, Sr, and K) in oceanic crustal hydrothermal circulation remains largely unknown. It is not surprising that published attempts at mass balance for recycling at arcs have resorted to unconvincing compositional averages or ranges. Yet, while the power of isotopic tracers in the arc context is obvious, as shown in Figure 15, the potential of the method has not been realized. With the mass flux calculation for the major global process of crust/mantle interaction mired in generalities at present, drilling offers the best chance for progress.

Drilling Strategy

From the above discussion it is clear that drilling adjacent to convergent plate margins is urgently needed to advance studies of convergent margin chemical fluxes and to

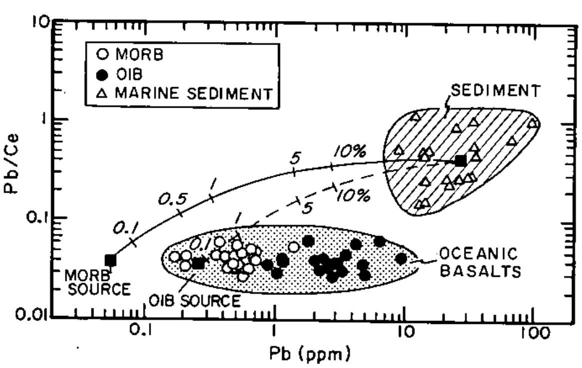

Figure 16. Pb concentrations and Pb/Ce ratios in oceanic basalts and modern marine sediments. Solid line sediment-MORB source mixing curve. Numbered ticks show percentage of sediment in the mixture. MORB source is assumed to have Pb and Ce concentrations 10 times lower than average MORB. Dashed line illustrates the effect of mixing sediment with a hypothetical OIB source having Pb and Ce concentrations 5 times higher than the MORB source. Addition of less than 1% sediment increases Pb/Ce ratios beyond the range observed. From White (1987).

better understand processes of crustal recycling. Such drilling should occur on the incoming plate, and in the forearc and backarc environments. Initially, on the down-going plate, several holes that penetrate at least through the zone of greatest hydrothermal interaction are essential. They should be located in older oceanic crust with minimal present-day hydrothermal activity, adjacent to well-studied oceanic island arcs. In the longer term, multiple holes through the sediment and the upper alteration zones of the crust in a variety of settings outboard of arcs will provide important new constraints on the arc volcanism problem. A significant portion of the input from the slab to the sources of arc magmas may come from the uppermost crust, and this crust also has the largest enrichments in incompatible elements - much higher than the more refractory and less altered gabbros in the lower crust. Thus, moderate basement penetration (300 m) in a variety of settings would make a substantial contribution to this area of investigation, particularly if there were other deeper holes that could be referred to for information about the chemical characteristics of the deeper crust.

Despite considerable work on subduction-related magmatic rocks, there is little consensus on the source of different elements in island arc rocks and on how their distinctive trace element compositions developed. Such questions are clearly fundamental to any attempt to establish geochemical fluxes, and they might be addressed by drilling (i) parallel to the trench on down-going plates where there are systematic lateral variations in sediment cover or in the chemistry of the volcanics from the neighboring arc; and (ii) around anomalies (hot spots or fracture zones) on the down-going plate that presumably should have some effect on the chemistry of the arc volcanics. By matching down-going chemical heterogeneities with variations in the arc volcanics it may be possible to constrain the sources of different elements in new continental crust.

To evaluate fluxes on the over-riding plate in a convincing way, clastic apron drilling must be preceded by base-line studies of volcanic and plutonic arc rocks, and of sediment derived from them. These studies should establish the arc-wide distribution of mineralogical, trace element and isotopic tracers. To evaluate the fluxes from the arc through time, there should probably be at least two holes in clastic wedges so that temporal correlation can be tested between them. Ideally the clastic apron drilling would be coordinated with deeper basement drilling on the arc basement as well. A transect of comparatively shallow basement holes across an arc-back-arc transition, carefully sited near one or two deep holes in the over-riding plate, would also be a useful contribution to constraining the net output fluxes at convergent margins.

PRIORITIES, RECOMMENDATIONS, AND DRILLING TIME ESTIMATES

The entire Working Group assembled at Strasbourg established an overall thematic priority and one top drilling priority.

The **thematic priority** is *to understand the present systematics of the solid earth circulation system, and the record of its action through time.* In this context, the single most important contribution would be drill holes through the entire thickness of the ocean crust. Since this objective is not technologically tenable at the present time, the specific first priority of the Working Group is *to develop the capability to drill such total crustal sections.* This capability has several aspects. It requires:

(1) a planning process that can encompass such a major, focussed long-term objective;

(2) a substantial program of engineering development that is insulated from the distractions of leg by leg operations;

(3) an inclusion of the necessary site surveys as essential

prerequisites for selection of the optimal drilling targets ;
(4) an allocation of substantial blocks of ship time for development of the capability of ultra-deep crustal penetration.

The Working Group did not agree on a ranking of the other priorities, since there was the recognition that since we are trying to understand an integrated geologic problem, all the parts of it are critical. Therefore the general objectives of mantle composition and dynamics, creation of ocean crust at spreading centers, and crust/mantle interactions at convergent plate margins all receive a ranking of second priority.

This general prioritization leads to the following discussion of allocation of drilling time for the two different options considered, namely *Option One*, a continuation of the present program with the *JOIDES Resolution*, or the ideal *Option Two* of adding a second ship for shallow drilling objectives. The geochemical mapping program to explore mantle composition and dynamics requires a significant number of holes, and hence would be possible on a large scale only with the two-ship option. In this case it would be vital for the second ship to be able to achieve some (on the order of 50 meters) basement penetration.

For the **top priority** objective of *developing the capability of total crustal penetration*, we estimate the need for two to three holes of 2000-3000 meters below basement (10 months drilling time), with the hope of extending one of them to Moho by the end of the ten-year period (an additional 12 months drilling time). We then estimate the allocation of approximately one year of drilling devoted to processes at spreading centers, and one year to the problem of fluxes at convergent margins. An additional year would be necessary for the deep drilling objectives associated with seamounts and oceanic plateaus. This totals almost five years of drilling time, but we note that all of these holes have overlap with the drilling objectives of the other Working Groups.

If there is a second ship capable of shallow basement penetration, then the geochemical mapping objectives become possible. Using TAMU time estimates, a single geochemical mapping hole in 4000 meters of water with 200 meters of sediment would take between 30 and 48 hours. If there were 40 working days in a two-month leg, this would imply the possibility of about 150 sites per year of drilling time. Three "ship years" using the ship designed for rapid, shallow penetration would then yield about 450 sites, which would make a substantial contribution. In many, though certainly not all cases, there would be overlap with holes used for the objectives of Working Groups 1 and 5.

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Fluid Circulation in the Crust and the Global Geochemical Budget

Prepared by WORKING GROUP 3 (see p. 10)

ABSTRACT

The circulation of sea water through the ocean crust is one of the Earth's major processes. Cooling the oceanic lithosphere and exchanging elements between the ocean and the crust, it provides a mechanism whereby changes in the Earth that affect oceanic lithosphere are relayed to the hydrosphere and thence to the atmosphere, with consequent effects upon the biosphere. Hydrothermal circulation in the oceanic crust, driven by forced convection at mid-ocean ridge axes and by free convection at ridge flanks, removes Mg from sea water and contributes Ca, and consequently influences the Earth's carbon budget. Only a small proportion of the Earth's carbon resides in the atmosphere as CO_2 and is dependent upon the levels of Ca, Mg and HCO_3 in the oceans. Convection at mid-ocean ridge axes is the most vigorous, with high temperature (350°C) chemical reactions, but the volume of water circulated through the much larger area of the ridge flanks is about twenty times greater, and although the system is less vigorous, with lower temperatures (150°C average), the influence of the ridge flanks upon the global chemical budget may be just as great as that of the ridge axes. The hydrothermal alteration of ocean crust may influence igneous processes at subduction zones, where the crust dehydrates as it descends into the Earth's mantle.

It is at subduction zones that the igneous ocean crust and the sediments lying on it lose water back into the ocean, through the expulsion of porewater by tectonic compaction and from dehydration reactions. The very high pore-fluid pressures that are generated in accretionary complexes play an important role in controlling the dynamics of the wedge, deformational processes and, probably, the partitioning of accreted and subducted sediment. Continental margins appear to host large gravitationally driven circulation systems of meteoric groundwater and saline fluids produced by the formation of evaporites or by fluids flowing through evaporitic rocks. Seeps have been discovered in many different settings at continental margins, and very preliminary estimates suggest that the magnitude of flow through continental margins could be greater than that through mid-ocean ridge axes. In the ocean basins, taken to be those parts of the oceanic lithosphere where convection no longer produces flow through the sea floor on a large scale, although there are localised occurrences, diffusional processes are capable of significant chemical exchange across the ocean floor in the absence of the physical movement of fluids.

Associated with water outflow from vents and seeps, in all environments are chemosynthetic biological communities based on H_2S, CH_4, H_2 and hydrocarbons. The density of biomass in these communities can be several hundred thousand times greater than typical densities on the "normal" ocean floor. Biological processes are important in diagenesis and cementation, and they can modify the chemistry of fluids and the permeability of vents and seeps.

A program of drilling over the next decade would investigate the active processes of hydrothermal systems and their alteration of the ocean crust with deep holes (3 km) to the hydrothermal reaction zones and shallow holes to define the circulation systems in both ridge axes and ridge flanks, with ridge axes having higher initial priority. Drilling in the accretionary complexes of tectonically active ocean margins would establish relationships between pore-fluid pressures and deformational processes, and investigate the degree to which fluids are removed from sediments and crust prior to subduction. At passive ocean margins, drilling may follow later in the decade when the circulation systems there are better explored and the objectives of drilling more clearly formulated.

Technological developments are required to meet the objectives of a drilling program to investigate fluid circulation in the crust. Deep holes into hard rock in oceanic crust and into overpressured formations in accretionary complexes are necessary, and at ridge axes, drilling may encounter temperatures as high as 400°C. For the program to be successful, it must have reliable techniques for measuring pore-fluid pressures, measuring temperatures, taking uncontaminated samples of pore-fluids and gases, obtaining complete recovery of alteration products, and determining the permeability structure of the region around drill holes. Surveys to site drill holes optimally in relation to geological structure and processes will be more intensive and employ more non-standard techniques than has been common in the past.

A program that is designed to allow the development of technology to keep pace with scientific requirements over the next decade, and which concentrates upon the fundamental elements of fluid circulation between the oceans and the crust, is called for. The Ocean Drilling Program will need to sustain programs to achieve long-term scientific goals, and this may require change in its ethos and organisation. Such change would be well justified in view of the achievement of understanding a major process of the Earth.

INTRODUCTION

The fundamental role of fluid flow in rocks in the processes of diagenesis, mineralisation, metamorphism and tectonics has long been appreciated. It is only comparatively recently, however, that fluid processes have been studied directly in active systems. Research over the last decade beneath the oceans has shown that the heat introduced into the oceanic crust by sea floor spreading drives a giant hydrothermal, fluid-rock reaction system at mid-ocean ridges. Large as this ridge axis hydrothermal circulation is, weaker convection at the ridge flanks, and other kinds of fluid circulation at the ocean margins, are almost certainly of greater magnitude. All these circulations redistribute elements within the crust and produce chemical fluxes to the oceans large enough to affect the ocean chemical balance and therefore to influence the ocean-atmosphere system which controls global climate. The mineralogical and chemical changes caused by fluid circulation through the oceanic crust are thought to affect the chemistry of magmas erupted when the ocean plate is subducted, and subsequently affect the weathering subcycle when these volcanics are weathered. Pore-fluid pressures in accretionary complexes influence deformation and accretion at active margins.

Biological processes are intimately associated with the sub-sea floor hydrologic circulation. An entirely new ecosystem based on a food chain starting with H_2S-oxidizing bacteria has been discovered at mid-ocean ridge hydrothermal vents. In the last few years biologic communities similar to those at mid-ocean ridges have been found to be very widespread, and occur at warm water vents on ridge flanks, cold seeps at accretionary complexes, hydrocarbon seeps, and cold saline seeps at continental margins. Most of these systems depend on nutrients carried to the sea bed by fluid circulation. Biological communities living within these flow systems provide mechanisms for transferring elements previously assumed to be immobile from the ocean crust to the global atmosphere/hydrosphere/ biosphere (AHB) system.

The circulation of water in rock and sediments beneath the sea floor occurs on a scale that makes it a first-order global geological process. It directly affects two major global chemical cycles: the cycle of elements through the atmosphere, hydrosphere and biosphere ; and the cycle of elements through the sediment, igneous crust, and uppermost mantle of the oceanic lithosphere. In the next decades we need to increase our knowledge of how hydrological, biological, chemical and tectonic processes interact in the ocean crust. In this chapter we try to place the hydrological processes of the ocean crust in a perspective that identifies the most important scientific questions. We do this by first defining the magnitude of fluid circulation through the oceanic crust and then establishing the chemical changes to the crust and oceans that these fluxes could produce. This approach makes gaps in our present knowledge painfully apparent. It also emphasizes the effectiveness of a hydrodynamic approach. If we can understand the general operation of hydrodynamic processes in the oceanic crust, we may, for example, with relatively few drill holes, be able to determine the alteration of the oceanic crust, and its volcanological consequences when the crust is subducted.

The discussion is of first-order scientific questions regarding pore-fluid circulation and the global geochemical budget. Therefore, the pore-fluid circulation systems of seamounts, hot spots, aseismic ridges, oceanic plateaus, or back-arc basins are not specifically addressed. Circulation in such areas could be of great interest for some problems such as the genesis of large massive sulfide deposits, and consideration of other scientific objectives might make some of these areas particularly attractive places to study examples of important ocean processes. From the perspective of the global geochemical budget, however, we believe that an understanding of the much larger general circulation in the oceanic lithosphere and its margins is essential. Similarly, little emphasis is put upon diffusional fluxes into or from the ocean sediments. These fluxes are important but have been well studied in the past decade.

After reviewing the scientific problems related to the hydrogeology of ocean crust, each hydrodynamic zone in the ocean is examined in greater detail and drilling objectives identified. Future technical requirements for drilling, logging and surveys are outlined. We also draw attention to areas that appear scientifically important but in which activity has only just begun. Finally a prioritized drilling program over ten years is presented.

A few words should be said about the process by which this chapter was generated. (1) First, a consultative white paper was prepared by the Working Group members that are listed as authors of this report. (2) This draft was used as a partial basis for extensive free flowing discussions in Workshop 3 at the COSOD II Conference. The prioritization of drilling objectives resulted from these discussions and a poll of the participants in Workshop 3. (3) Finally the Working Group rewrote the initial white paper to reflect the Strasbourg discussions and decisions, in which we were aided by the many written comments provided by the participants in the Workshop, too numerous to acknowledge individually, and especially J.K. Whelan and C.K. Paull.

Physical Flow Processes

Four physical processes cause fluid circulation in the ocean crust :

(1) At the ridge axis, magma maintains steep horizontal temperature gradients in the surrounding crust. These gradients drive a vigorous *forced* convection. It is this circulation that vents ~350°C fluids at or very near the ridge axis, producing the "black smokers" that occur on both fast- and slow-spreading ridges.

(2) A weaker *free* convective circulation continues between a few kilometres and as much as 1000 km from the ridge axis (Fig. 1). In this region the oceanic crust is permeable enough that the critical Rayleigh number (which controls the onset of free convection) is exceeded by the heat flow into the base of the crust from the cooling oceanic lithosphere. Depending on the rate of sea floor spreading, and the permeability of the oceanic crust, these free convection cells may migrate through the oceanic crust or may move with it as if they were "attached".

(3) Simple physical compaction accompanying sedimentation produces negligible flow into the ocean. Overall, the sedimentary section gains water as it grows. At passive ocean margins, however, differential loading produced by laterally varying thicknesses of sediment overburden can drive pore fluids out into the ocean, although there is a net gain of water into the crust. Only at active ocean margins, where tectonically induced compaction during the processes of subduction and accretion expels water into the ocean, is there a net loss of water from the crust.

(4) At a continental margin, meteoric groundwater moving through the continental crust, driven by a gravitational head, may be expelled into or cause circulation in the oceanic crust given a favourable aquifer geometry. Flow can also be driven by density gradients produced by evaporite formation or from flow of groundwater through evaporites.

The four physical processes producing aqueous movement in the oceanic crust (forced convection, free convection, compaction, and gravitationally induced hydrologic flow or haline convection) tend to apply to separate regions of the oceanic crust, as illustrated in Figure 1. This justifies discussion of pore-fluid circulation in hydrodynamic regions lying at increasing distance from an active oceanic ridge. The "ridge axis region" is defined to be the region close to the ridge where fluid circulation is caused by forced convection. The "ridge flank region" is the part of the oceanic crust where free convection occurs. The "ocean basins" are defined as regions of diffusive flux where pore-fluid convection in the oceanic crust has ceased. Finally, active and passive "margins" refer to

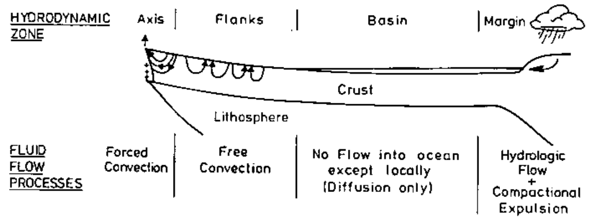

Figure 1. Hydrodynamic zones and fluid flow processes on oceanic plate.

Table 1. Permeability of ocean crust.

Location	Permeability	Depth of circulation	Criteria	Comments
Near ridge axes ↑	$<10^{-14}$ m^2	5 km	Permeability greater than this would reduce heat flow in inflow area below observed values.	Approximate calculation based on Nusslet and Rayleigh numbers (Anderson, 1977).
	$<3 \times 10^{-15}$ m^2	3 to 5 km	" "	Convection calculation which includes temperature-and-pressure-dependent water viscosity and density (Fehn & Cathles, 1979).
Average permeability of crust decreases 10^1 to 10^2 ↓	3×10^{-16} m^2	3.5 km	Pattern of heatflow in 0.14 to 1 my old crust in the Galapagos area. 7 km spacing of high and low heat flow bands suggests convection to 3.5 km depth. 5 HFU amplitude gives permeability.	
At flank/basin	$<2 \times 10^{-16}$ m^2 Atlantic (80 my) $<5 \times 10^{-17}$ m^2 Galapagos (5 my)	5 km	Critical Rayleigh number of 27 not exceeded under heatflow of 11.5/t (my) HFU.	Age of crust where observed joins theoretical conductive heatflow given by Anderson et al., 1977.
Permeability change with depth : DH 504B drilled into 5.9 my crust 200 km south of Costa Rica Rift	10^{-13} - 10^{-19} m^2	0-150 m	Uncemented pillow basalts, Layer 2A	Anderson et al., 1985.
	10^{-17} - 10^{-15} m^2	150-550 m	Cemented pillow basalts & dykes, Layer 2B	Leg 111 Shipboard Sci. Party (1987)
	$<10^{-17}$ m^2	500 m to 1300 m	Sheeted dykes, Layer 2C	No convection indicated below 200 m depth by drillhole temperature profile.
Near trenches	$>3 \times 10^{-16}$ m^2	>8 km	Flexing of oceanic plate by subduction causes very deep fractures, unusually strong convective cooling. Petrology suggests deep magma chambers. Deep convection taps.	Abbot & Fisk (1986).

areas where tectonic deformation of sediment or hydrologic or salinity gradients could produce fluid movements in the oceanic crust.

The amount of fluid circulation caused by each of these processes can be estimated as indicated in Table 1. The magnitudes of pore-fluid circulation in each region are compared in Figure 3. The estimates in Figure 3 are *very* crude (reader or user beware) but serve to indicate where significant chemical fluxes from or to the oceans *may* be occurring as the result of pore-fluid movement. It should be noted that the diffusional flux of elements from sea water into oceanic sediments is at least as large as the fluxes associated with pore-fluid movement. (For example, if the effective diffusional porosity of the uppermost 1 m of sediments is 10^{-6} cm^2/sec, depletion of an element in sea water at 1 m sediment depth will drive a diffusive flux equivalent to that caused by a sea water inflow of 3 cm/year, which is a strong rate of convective recharge.)

Hydrothermal circulation through the oceanic crust at mid-ocean ridge axes occurs on a very large scale compared with terrestrial hydrothermal systems. This may not be immediately apparent from the magnitude of the ridge discharge, 24 km^3/yr (Table 2), but it may be appreciated if it is remembered that hydrothermal activity is related to the magmatic introduction of heat into the earth's crust. Over the past 200 million years sea floor spreading has covered 3/4 of the earth's surface with lavas >5 km thick. No other volcanic process is comparable to this in magnitude. For this reason alone ocean hydrothermal circulation is important in global geochemical balances.

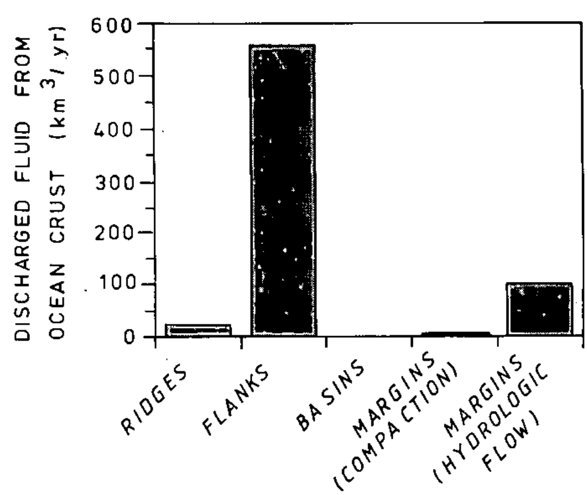

Figure 3. Estimates of the flux of sea water through or out of the various hydrodynamic zones in Figure 1, and the physical processes driving fluid circulation.

Table 2. **Fluid fluxes through the ocean plate (± factor of 3).**

Hydrodynamic zone		Flux	Process	Method of computation and reference
Ocean ridges		24 km^3/yr	Forced convection	Heat lost by 5 km thick oceanic crust in cooling 1100°C set equal to heat carried out by 330°C sea water. Assumes crust cools at ridge axis. Crustal heat capacity = 0.6 cal/cm^3-°C. Estimate compatible with Wolery and Sleep's (1978) estimate for convective heat loss between 0 and 1 my.
Ocean flanks		560 km^3/yr	Free convection	Same as above but heat source is 50% cooling of 100 km thick oceanic litosphere and venting at 150°C, not 350°C.
Ocean basins		~0 ?		
Margins :	Active (and passive)	1 km^3/yr (+ deltas)	Sediment compaction	2.6 km^2 plate subducted per year with 1000 m thick sediment load whose porosity is reduced 40% by subduction processes.
	Passive (and active)	100 km^3/yr	Hydrologic flow	33% of rainfall on area equal to 5% of the continental shelves infiltrates and half of this discharges into the ocean in submarine springs.

Convection circulates more fluid through the oceanic crust in the off-axis "ridge flank" regions than in the "ridge axis" region (Fig. 3). Free convection on the ridge flanks is slower than the forced convection that occurs at the ridge axis, but it is cumulatively greater, because the initial heat reservoir in the cooling oceanic lithosphere is roughly ten times bigger than the heat reservoir of the oceanic crust that drives the axial circulation. The hydrologic flux into the oceans at continental margins could be relatively large, because rainfall on continents is large. Haline convection at passive margins could also be large, but there is no observational basis for estimating its magnitude at present.

Chemical Processes

Inorganic Chemical Cycles

Pore-fluids circulating through the oceanic crust produce chemical fluxes to and from the oceans which, unless balanced by other fluxes, could alter the chemical composition of the oceans. The fluxes that have been most studied to date are those associated with river discharge to the oceans, sedimentation from the oceans, and, most recently, the high temperature 350°C discharge to the oceans at mid-ocean ridge axes. The relative importance of the chemical fluxes can be illustrated schematically by the elements involved in the chemical weathering/inorganic CO_2 cycle : bicarbonate and its principal charge-balancing cations Mg^{++} and Ca^{++}.

The weathering cycle involves : (1) The dissolution of atmospheric CO_2 in rainwater to form carbonic acid. (2) The reaction of carbonic acid with exposed rocks (weathering) to produce bicarbonate, HCO_3^-, cations such as Mg^{++} and Ca^{++} and solid residues. (3) Transport of these ions in solution to the oceans by rivers and underground seepage. (4) Exchange of Mg^{++} for Ca^{++} perhaps mainly in the mid-ocean ridge hydrothermal system. And finally (5) reaction in the oceans of Ca^{++} and HCO_3^- to precipitate calcite and release CO_2 back to the atmosphere.

The weathering cycle is particularly important because over millions of years the dynamic balance of the carbonate-silicate geochemical cycle (reactions involving organic C and S are included) is one of the important external forcing factors controlling the concentration of CO_2 in the atmosphere. Because the amount of atmospheric CO_2 is very small compared to the amount of carbon in carbonates and organic matter, even small perturbations between the fluxes in the carbonate-silicate geochemical cycle could cause significant changes in the atmospheric CO_2 concentration. Tectonic processes can perturb the delicate balance of the cycle. An increase in the rate of sea floor spreading, for example, could lead to an increased rate of discharge of Ca^{++} at mid-ocean ridges, and an increased exchange of C between the earth's surface, crust and mantle, and for all these reasons an increase in CO_2 concentration in the atmosphere. It has been suggested that such processes caused the long-term climate changes, recorded in the marine and continental sedimentological and biological record, in the past 100 million years (Berner *et al.*, 1983 ; Lasaga *et al.*, 1985).

Table 3 estimates the flux of Mg^{++} and Ca^{++} to the oceans from the various hydrologic zones of Table 1 and Figure 1. The ridge zone makes an important contribution to Mg balance in the oceans. Before the ridge contribution was appreciated, it was known that the rivers were introducing more Mg to the oceans each year than the sedimentation sink could remove (Drever, 1974). It is clear from Table 3 that other (non-ridge) ocean hydrologic fluxes could significantly contribute to the ocean Mg^{++} and Ca^{++} budget. In particular, if flank convection approaches 560 km^3/yr, it could remove as much Mg as the ridges remove. The ridge flanks could be as geochemically important as the ridge axes. It is also clear from Table 3 that ocean margin seeps could contribute significantly to the ocean Mg and Ca balance, although this is much more difficult to assess because of our present ignorance of both the magnitude and chemistry of these fluxes.

This discussion emphasizes how poorly defined is the inorganic ocean chemical cycle. Fluxes in the ridge flank and margin zones are particularly poorly constrained. Major, perhaps at times partially balancing, chemical fluxes are possible in both areas. For different elements the hydrodynamic zones have different relative importance. The efficient stripping of ^3He from ridge crest volcanics by hydrothermal activity points to a dominant role for the ridge axis in degassing the mantle, whereas ridge flank hydrothermal systems equal axis systems in the chemical exchange of Mg and F between sea water and the crust.

Inorganic Alteration of the Oceanic Crust

Sea water is highly oxidized and enriched in Mg, ^{18}O, and ^{87}Sr compared to the composition of a fluid of similar salinity in equilibrium with basalt at low (~50°C) temperatures. Inflow of sea water thus oxidizes the oceanic crust, and enriches it in Mg, ^{18}O, and ^{87}Sr. The total amount of oxidation and enrichment provides, in principle, a redundant measure of the total amount of sea water that has reacted with the crust at a particular location.

The isotopic profiles in ophiolites such as the Semail have been interpreted to reflect the inflow of sea water with equilibration at ~3 km depth (Cathles, 1983 ; Bowers and Taylor, 1985) ; see also Spooner *et al.*, 1977a,b), or a separation

Table 3. Concentrations and fluxes of HCO_3^--complexed Ca^{++} and Mg^{++} in river and ocean discharges. The fluxes are given as a percent of the river flux (in parentheses) to allow easy comparison. Ocean water contains ~10 millimolal Ca^{++} and ~54 millimolal Mg^{++}. River concentrations are from Berner *et al.* (1983). Ridge concentrations are from Von Damm *et al.* (1985). Flank concentrations are from Maris *et al.* (1984). Fluxes from ridge axes estimated by Von Damm *et al.* (1985) using fluid discharges derived from ^3He anomalies (Jenkins *et al.*, 1978) are six times greater. Fluxes from continental margins are entirely hypothetical.

OCEAN CHEMICAL BALANCE

RIVERS
37 400 km^3/yr

$[Ca^{++}]$	=	0.33 millimolal	+ 12.5 x 10^{12} mole/yr
$[Mg^{++}]$	=	1.14 "	+ 5

RIDGE AXIS
24 km^3/yr

$[Ca^{++}]$	=	20 out	10.4 in	+ 0.23 (2% River)
$[Mg^{++}]$	=	0 out	53.9 in	- 1.3 (-26% R)

RIDGE FLANK
560 km^3/yr

$[Ca^{++}]$	=	12 out	10.4 in	+ 0.9 (7% R)
$[Mg^{++}]$	=	52 out	53.9 in	- 1.1 (-21% R)

CONTINENTAL MARGIN
100 km^3/yr is the flow estimated for meteoric groundwater. If similar volumes of flow apply to the following processes, their effect would be as tabulated.
Discharge of evaporated seawater that has reacted with sediments similar in composition to an oil field brine

$[Ca^{++}]$	=	715 (OFB)	+ 71 (+570% R)
$[Mg^{++}]$	=	33 (OFB)	+ 3.3 (+66% R)

Haline convection and exchange of Ca^{++} for Mg^{++}

$[Ca^{++}]$	=	10 in	64 out	+ 5.4 (+42% R)
$[Mg^{++}]$	=	54 in	0 out	- 5.4 (-108% R)

of convection into an upper 3 km cell and a lower 3 km cell (Gregory and Taylor, 1981). The oxygen isotopic enrichment occurs above 3 km where sea water reacts with basalt at low temperatures and high water-rock ratios. The isotopic depletion below 3 km occurs as the result of higher temperature, lower water-rock ratio interaction at the edges of ridge magma chambers and in the ridge and flank zones. The exchange of ^{18}O between sea water and oceanic crust in opposite senses, at high and at moderate to low temperature, effectively buffers the $\delta^{18}O$ value of sea water (Muehlenbachs and Clayton, 1976 ; Gregory and Taylor, 1981 ; Muehlenbachs, 1986). Cycling sea water through oceanic crust influences the $^{87}Sr/^{86}Sr$ ratio in sea water. Changes in the rate of sea water cycling are thought to have been one of the causes of the variations in the Sr isotope composition of sea water over the Phanerozoic (Peterman *et al.*, 1970 ; Burke *et al.*, 1982).

Perhaps the most important unknown quantity at the present is the relative amount of sea water circulation and isotopic alteration that occurs (1) at the ridges (including inflow up to ~5 km from the ridge axis) and (2) in the flank zone. The relatively uniform isotopic and chemical alteration that has been observed in ophiolites and the interpretative modelling that has been done suggest that a reasonably unambiguous measure of the amount of sea water inflow in the ridge axis and flank zones could be obtained by comparing the chemical and isotopic alteration in two 3 km deep holes, one drilled about 5 km from the ridge axis and the other at the far edge of the flank zone.

Organic Chemical Cycles

The organic and inorganic carbon cycles are closely coupled by biological and thermal processes operating on biogenic debris. Most living organisms oxidize reduced carbon compounds to CO_2 and water, transferring electrons to the more oxidized parts of the system. This general reaction occurs in all animals and plants, including microorganisms whose specific oxidation-reduction reactions depend on the biological species involved. In sediments, these reactions often involve transfers of various nutrients and food sources between organisms in a community. A variety of different electron acceptors are used in these biological redox reactions, including oxygen, nitrate, sulphate, and carbon dioxide in successively deeper and more oxygen-depleted sediment zones. Thus the biological sediment carbon cycle feeds directly into biological systems involving elements such as sulphur, nitrogen, phosphorus, and iron at greater depths.

The AHB (atmosphere/hydrosphere/biosphere) contains about 3 x 10^{15} kg of organic carbon and about 37 x 10^{15} kg of inorganic carbon (Sundquist, 1985). These amounts are relatively small when compared with the carbon reservoir in sediments of about 8 x 10^{17} kg. Transfer of even a very small part of the comparatively huge rock reservoir of carbon to the AHB could possibly produce large changes in the AHB carbon content. Des Marais (1985) has estimated the flux of mantle carbon out of the ocean crust by multiplying the $C/^3He$ ratio measured in mid-ocean ridge basalts and vent fluids (they are "about" equal) by the measured total yearly hydrothermal ^3He flux to the oceans. Thus estimated, the mantle carbon flux is between 12 and 96 x 10^9 kg/yr. The mantle flux could affect the AHB carbon reservoir on timescales of ~10^6 years (= total carbon content of the AHB of 40 x 10^{15} kg divided by the average flux of 54 x 10^9 kg/yr).

Sedimentation rates, especially at ocean margins, may be great enough for reduced carbon to escape oxidation and be buried. As burial progresses and these sediments are warmed, petroleum, hydrocarbon gases (principally methane), and CO_2 are produced. A proportion of these gases will accumulate in structural and stratigraphic traps or as hydrates (clathrates) in the upper few hundred metres of the sediment column.

Organic and related element fluxes caused by fluid flow in the ocean crust are large enough that they must be considered in global geochemical cycles. Under some circumstances fluxes from the ocean crust could dominate or cause climatically important chemical changes in the AHB. At the very least fluid circulation processes provide a mechanism whereby sediments and deeper magmatic rocks can buffer the AHB carbon system.

Petrologic Chemical Cycle

This topic is the subject of the chapter on mantle/crust interaction in the COSOD II Report and will not be dealt with in detail here. Magma is erupted or intruded to form crust with a very restricted and fairly well known chemical composition at mid-ocean ridges. The crust is modified in two ways as it moves from the ridges to the trenches where it is subducted and in part returned to the mantle : (1) It is hydrated and chemically altered by sea water convection. (2) It has sediment added to it, some of which is scraped off into accretionary wedges at the subduction zones. The hydration and chemical changes (both by sea water convection and the addition of sediment) mainly control the chemistry of magmas produced during subduction. In fact it is the hydrated nature of the crust that enables the cold subducted plate to melt the mantle rather than freeze it.

Understanding (1) the hydrology of alteration, and (2) the interactions between hydrology and tectonics that control the amount of sediments scraped off at subduction zones, is probably the only feasible way to characterize the chemical changes of the oceanic crust that control mantle-crust interaction and arc volcanism. To try to define the alteration of the oceanic crust by grid drilling in the absence of some hydrodynamic understanding would almost certainly prove wasteful and might be impossible. Similarly, the permeabilities of the crust and sediments are linked through generation of excess pore pressure to the deformation and removal of sediment from the oceanic crust at subduction zones.

Biological Processes

Prolific deep-sea benthic communities associated with fluid circulation in the oceanic crust have been discovered virtually everywhere that fluids discharge into the oceans. They have been found at mid-ocean spreading axes (the Red Sea is a very special case, where abiotic zones were evolved due to high temperature, anoxia and high concentration of toxic heavy metals), back-arc and sediment-smothered spreading centres, accretionary complexes at subduction zones, and in tectonically passive areas, such as sulphur-rich hypersaline seeps at the foot of the Florida Escarpment and hydrocarbon seeps on the continental slope off Louisiana. They even occur in the shallow areas of high organic loads, whether they are induced naturally (mangrove swamps, salt marshes), or artificially by human impact (sewage outfalls). Vent and seep-dependent communities have been reported from continental shelves (Bright *et al.,* 1980 ; Kleinschmidt and Tschauder, 1986). Fossil records of the biological communities are reported from Japan and America (Boss and Turner, 1980) and from Cretaceous Semail ophiolites in Oman (Haymon *et al.,* 1984).

These dense biological communities, though very localized, are remarkable in their extraordinarily high standing stocks and metabolic productivity. Chemolithotrophic bacteria *per se,* or animals in symbiosis with the chemosynthetic microorganisms, can metabolize reduced compounds present in high concentrations in the venting solutions, and maintain high growth rate and metabolic activities. The net production of benthic organisms at the hot and cold vent fields at several tens of kg/m^2 is estimated to be 5 to 6 orders of magnitude higher than that of normal ocean basins where benthic life is primarily sustained by the "rainfall" of photosynthetic products.

Bacteria can utilise H_2S, CH_4, NH_4, H_2, and hydrocarbons ; different species operate aerobically (requiring oxygenated bottom waters) and anaerobically (requiring only relatively oxidized chemical species such as sulphate). Higher order species feeding off or in symbiosis with the bacteria selectively concentrate various elements. Methane concentrations of 10 000 nl/kg have been measured in water samples from clam beds in the Hatsushima site of Sagami Bay in Japan. The soft parts of vent clams contain up to 3.4 wt % sulphur. Thus biological activities modify the chemical flux at sites of fluid discharge into the oceans by (1) selective scavenging, (2) incorporation of elements into sediments, and (3) selective elution from sediments.

Much of the biological work is still in the basic exploration stage. Only recently has it been appreciated how widespread biologic activity is at ocean seeps. The most urgent problem is to estimate the extent to which vent communities modify the chemistry of the fluid outflow. To do this it will be necessary to distinguish what would be the "normal" chemistry of discharging fluids in the absence of biological activity. Uncontaminated solid and fluid sampling at depths of ~10 to 100 m (by drilling or other means) is necessary to make this determination. It will be particularly important to assess how deep biological activity may persist at the present time, and to develop reliable indicators of the relative importance of thermogenic and biologic processes in the past.

Biological processes are important in diagenesis and cementation. For example oxidized methane and/or other hydrocarbons are the source of carbon in carbonate cements found in the seeps. Biological activity can thus modify the permeability of vents. Evaluation of the vents ultimately will require very detailed studies of the vent plumbing system, fluid mixing, etc., and projections of how the plumbing system changes with time as the result of mineral precipitation and biologic activity.

Biological studies at ocean vents may be useful in other ways. Alternations of microstructures within the outer shell layers of vent bivalves have been interpreted as closely reflecting fluctuations in the rate of vent discharge. Theory and laboratory experiments suggest that the temperature, pH and chemical gradients encountered by circulating pore fluids at mid-ocean ridge axes may be appropriate for inorganically synthesizing amino acids and single cell cyano-compounds. Demonstration that this is occurring at ridges today would provide important support for the hypothesis that life originated at mid-ocean ridge hydrothermal vents.

Crustal Permeability

The permeability of the oceanic crust and its changes in time and space control the locations of the zones in Figure 1, the rate and depth of fluid circulation within the convective zones, the temperatures and depths and thus the kinds of chemical reactions that are encountered by the pore fluids during circulation, and the focus and rate (and thus the chemistry) of the fluids that discharge from the crust into the ocean. It is such a fundamentally important parameter to all we have so far discussed, that it warrants separate discussion.

Permeability is a physical parameter unusual in *commonly* having a very large geological range and rapid geologic variability. Coarse sand has a permeability of $\sim 10^{-10}\ m^2$; clay a permeability $<10^{-17}\ m^2$. Clay and sand often occur in adjacent sedimentary layers, producing a highly anisotropic permeability. Fractures can make otherwise very low permeability igneous rocks very permeable. Structures thus exert considerable influence over fluid migration pathways as any economic geologist knows. Alteration may decrease or increase permeability depending upon whether the reactions are volume-filling or reducing. There is a very strong relation between permeability and fluid pressure when the fluid pressure approaches lithostatic. Fluid pressures approaching lithostatic greatly weaken rocks or sediments (a phenomenon important in controlling the geometry of accretionary prisms). Faulting promoted by geopressuring produces structures that may permanently change the permeability pattern. From the point of view of thermal modelling of ocean hydrothermal systems, permeability can be considered uniform if major "flow" fractures are a few 100 m or less apart. Alteration modelling must take into account fracture control if fractures are more than a few centimetres apart. Permeability is thus a parameter that can be expected to have complicated local variations and a rich history of change. Permeability must be investigated on a setting by setting basis and will require substantial resources and investigative persistence to characterize appropriately even in one setting.

What is presently known about the permeability of the oceanic crust is summarised in Table 1, and appears to range from $\sim 10^{-14}\ m^2$ to $\sim 10^{-17}\ m^2$. Table 1 suggests for example that the permeability of the oceanic crust near the ridge axes is probably $\sim 10^{-14}\ m^2$. Isotopic studies of ophiolites indicate that convection occurs through the crust down to the Moho (Gregory and Taylor, 1981). Heat flow in the oceanic plate indicates that such deep convection occurs at the ridge axes and that the entire crust is cooled by vigorous forced convection within a few kilometres of the ridge axis. There is some hydration of ultramafics below the Moho (MacDonald and Fyfe, 1985) but fluid penetration of the sub-crustal lithosphere is minimal.

Convection causes mineral precipitation that progressively plugs the permeable fractures. Observations at Site 504B show that plugging has occurred at the bottom of the pillow basalt and top of the sheeted dyke layers in that 3 my old portion of the oceanic crust. The permeability has been reduced in these zones to $<10^{-17}$ m^2. The heat flow pattern around 504B suggests that convection may be continuing at deeper levels. Permeability in the 504B area may thus return to levels ~3×10^{-16} m^2 at depths below 1.5 to 2 km. Flexure of the oceanic plate near trenches may cause deep fractures to reopen and even extend significantly into the lithosphere. Convection may resume or be re-accelerated near trenches and may even penetrate significantly into the lithosphere. The general merging of measured heat flow with values expected for the conductive cooling of the oceanic plate (Fig. 2 ; Anderson *et al.*, 1977) suggests that convection typically ceases to affect surface heat flow between 150 and 800 km from ridge axes.

How the permeability of the crust is reduced by chemical alteration, and convection is abated, and how permeability and convection are rejuvenated by tectonic forces near ocean margins are subjects that need to be generally addressed in the next decade.

Applications

Studies of the hydrogeology of the ocean crust, in the broad sense presented above, could contribute insights to many practical or applied problems. For example :

(1) An understanding of the time variability of ocean ridge hydrothermal systems could identify the factors that promote the formation of particularly large massive sulphide deposits and thus aid exploration for economic deposits on land.

(2) An understanding of flow regimes at active and passive continental margins could assist hydrocarbon exploration as it moves further offshore.

(3) The compaction of delta sequences, the spatial distribution and rate of outflow, and how this flow is controlled by the geologic framework, is fundamental to oil migration and accumulation. Studies of appropriate basins in the oceans can take advantage of the low thermal noise of the oceans and the accessibility of the oceans for detailed heat flow and other ship-based geophysical surveys.

(4) Detailed understanding of the role of fluid pressure in the development of structures in accretionary wedges could aid the interpretation of structures that trap hydrocarbons and localise mineral deposits.

(5) Biological studies of ocean sediments, especially the animal communities and carbonates that reveal the modern and ancient pathways through which methane, hydrocarbons, and other nutrient-bearing fluids escaped during diagenesis, could provide insights useful in understanding hydrocarbon migration and accumulation.

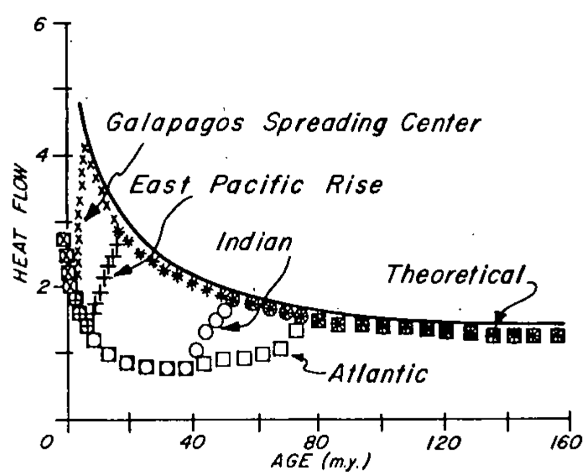

Figure 2. The discrepancy between observed and expected heat flow on the oceanic plate was the first clear indication that sea water was convecting in significant volumes through the oceanic crust. The heat flow observed through ocean sediments joins that theoretically expected for the conductive cooling of the oceanic lithosphere, indicating that convection has ceased or very significantly slowed, at various times and distances from ocean ridges. At the Galapagos convection "ceases" about 150 km of the ridge axis. In the Atlantic convection "ceases" about 800 km from the axis. From Anderson *et al.* (1977).

HYDROGEOLOGY OF THE OCEANIC LITHOSPHERE

Mid-Ocean Ridge Axes

At the ridge axis, circulation is driven by high (magmatic) temperature heat sources, and occurs at temperatures of up to 400°C. The volume of water involved in these high-temperature systems is large, with water/rock ratios (thermally defined) as high as 2/1. In these systems, heat is transported with extreme efficiency because of the inviscid and buoyant character of water at such elevated temperatures. The high temperatures of fluid circulation provide conditions for extremely efficient chemical exchange and transport as well. Evidence for this is found in the occurrence of large deposits of poly-metallic sulphide minerals where high-temperature hydrothermal fluids have ventilated through the sea floor. Axial hydrothermal systems are important for a variety of reasons : they have produced many of the World's economic mineral deposits now found on land ; they undoubtedly have a profound effect on the geochemical budget of the World's oceans ; and they must have a significant effect on the ultimate composition and mineralogy of the crust by the time it is recycled back into the mantle at subduction zones.

At present, observations that constrain models for predicting the physical and chemical conditions in axial hydrothermal systems are highly limited. Deep fluid chemistry has to be estimated from vent fluids that have experienced various degrees of mixing with fluids from shallower levels (*e.g.* Edmond *et al.*, 1982). Heat flow measurements are normally impossible to make in axial regions due to the lack of sediment cover, and hence the plan of groundwater circulation is difficult to describe. Thermal and chemical plumes in the water column are quickly diluted and are difficult to use in any accurate quantitative way to assess the distribution and size of hydrothermal discharge sites (*e.g.* Crane *et al.*, 1985 ; Lupton *et al.*, 1985 ; Baker and Massoth, 1986 ; Little *et al.*, 1987). Observations in ancient systems (*e.g.* Spooner, 1977) are contaminated by structural and geochemical overprints superimposed in off-axis and later emplacement settings. Crustal drilling into a currently active system, including sampling, logging, and subsequent downhole observations, provides the best way to gain a clear understanding of the physics and chemistry of high-temperature hydrothermal circulation.

A few characteristic elements of ridge-axis hydrothermal systems are depicted in Figure 4, where schematic cross sections through sediment-free and sediment-covered ridges are shown. The former is by far the most typical situation, but the latter, exemplified by Guaymas Basin of the Gulf of California (Lonsdale and Becker, 1985), Escanaba Trough of the Gorda Ridge (Morton *et al.*, 1987), and Middle Valley of the Juan de Fuca Ridge (Davis *et al.*, 1987), are important in providing opportunities for studying active high-temperature systems and major mineral deposits through the Ocean Drilling Program.

The main difference between hydrothermal systems at sediment-free and sediment-covered ridge axes is that in the latter case, the recharge and discharge of crustal fluids are inhibited by the relatively low-permeability sediment cover. As a result, hydrothermal fluids have a much longer residence time at high temperature, and can interact efficiently with a much greater volume of crustal rock. Other significant differences are that the sediment cover can serve to focus and prolong discharge at a given site, perhaps through multiple episodes, and provide a porous medium through which discharging fluids must pass, lose heat, and chemically interact. In fact, sediment cover appears to have a far greater influence on fluid and mineral chemistry (von Damm *et al.,* 1985 ; Davis *et al.,* 1987) than do spreading rate or other tectonic variables.

For the purpose of this discussion, the flow of hydrothermal fluids through the crust in both environments has been broken into a few characteristic elements, including zones of (l) recharge, (2) downflow, (3) high-temperature reactions, (4) upflow, and (5) discharge. In typical sediment-free ridge-axis settings, vigorous discharge is only known to occur at discrete, sparsely distributed sites along the central rift zone (*e.g.* Ballard *et al.,* 1981 ; Hekinian *et al.,* 1985 ; McConachy *et al.,* 1986 ; USGS Study Group, 1986) where extensional faulting is concentrated, and crustal permeability is undoubtedly enhanced. No vigorous discharge has been observed in off-axis locations except from systems associated with seamounts. The width of the rift zone varies with spreading rate, and with distance along axis at any given rate (*e.g.* Macdonald, 1983) ; at intermediate to fast rates, central rift zones are commonly only a few hundred meters in width. Widths of potential heat supply zones, *i.e.* acoustically imaged axial magma chambers (*e.g.* Morton and Sleep, 1985 ; Detrick *et al.,* 1986), are on the order of 1-2 km. Depths to typical axial reflectors are on the order of 2-3 km. Estimates of crustal permeability lean heavily on measurements at DSDP Sites 395A and 504B (Hickman *et al.,* 1984; Anderson *et al.,* 1985) and are probably not representative of young, relatively unaltered, highly fractured, and tectonically active axial regions. Very little is known about the recharge and downflow geometry, or about the nature of the primary reaction zone.

Several models have been put forward to describe the physics of axial fluid circulation, the nature of chemical exchange and heat collection at depth (*e.g.* Lister, 1974, 1984 ; Lowell, 1975 ; Sleep and Wolery, 1978 ; Cann *et al.,* 1985 ; Fehn *et al.,* 1983) ; they lean to various extents on poorly constrained assumptions, on basic physics, on observations in ancient systems, and on the limited observations of hydrothermal systems at ridge crests. They involve fluid flow in two-dimensional fractures, three-dimensional porous media flow, interaction between hydrothermal fluids and a convecting magma chamber, and thermal contraction cracking and hydrothermal penetration of hot rock units. All have important implications for the chemical and thermal balance of ridge-crest hydrothermal circulation, and need testing. ODP drilling can undoubtedly provide many additional constraints, and new insights into the various elements of axial hydrothermal systems.

Drilling Strategy

For the reasons stated above, it would be desirable to drill in both sediment-free and sediment-covered axial environments. In both, observations of the physical and chemical conditions in the high-temperature reaction zone are of highest priority. This will involve deep drilling (c. 3 km), with the goal being penetration to a well-imaged magma or unfractured hot-rock unit.

A deep hole at a sediment-free ridge crest would be best sited in the axial rift but some distance (hundreds of meters along axis) away from a discharge site. Such a hole would presumably penetrate a "zero-age" recharge zone above the high-temperature reaction zone, and would provide a reference section to which the alteration at off-axis sites (see below and next section) can be compared. In penetrating the crust of the axial rift zone, the hole would allow the permeability of the fractured axial zone to be characterised and compared with that of existing and new ridge-flank sites.

A deep hole in a sedimented ridge environment would be designed to penetrate high-temperature (>350°C) crust throughout the section, so that a portion of the high-temperature crust-fluid system could be studied even if full penetration to the primary reaction zone is not achieved. As in the case of the sediment-free axial site, the hole could be positioned to allow the influence of rift faults on crustal permeability to be studied.

Another high-priority objective should be to characterise the nature of sediment-hosted mineralisation with arrays of shallow holes in discharge zones. Contrasting modes of occurrence are found in Guaymas Basin, Escanaba Trough, and Middle Valley, with upflow paths through various types and amounts of sediments (terrigenous and biogenic, tens to hundreds of meters) and volcanics (major axial volcanoes, faulted basement outcrops, and dykes and sills) and a strong case can be made for characterising each of these sites of present or past discharge and mineralisation.

Drilling a similar array of shallow holes in a sediment-free axial discharge zone would be valuable in order to characterise the plumbing beneath a high-temperature vent. This would allow the nature of shallow-level mixing, and the history of discharge (bearing in mind the strong effects of retrograde reactions), to be studied.

Finally, a deep-penetration hole in the distal (off-axis) recharge zone would be valuable for assessing the integrated effect of recharge alteration, and thus in estimating the total quantity of fluid that circulates through the crust in the axial region. This site would be best placed several kilometres away from the axis, but in an area still under the influence of high-temperature axial heat sources and at a location that had never experienced high-temperature upflow or discharge.

Mid-Ocean Ridge Flanks

The difference between the pattern of heat flow from oceanic lithosphere and that expected from purely conductive models reflects the substantial convective transport of heat by fluid on mid-ocean ridge flanks (Figs. 2, 3). As has been indicated previously in this chapter, simple physical models (Table 1) suggest that the discharge associated with this flow could be more than an order of magnitude larger than that associated with ridge-crest fluid circulation, because of the immense heat reservoir provided by the lithosphere over the large area of the ridge-flank zone. Cooling of this ridge flank zone accounts for 90% of the non-conductive heat loss from the lithospheric mass (Sleep *et al.,* 1983). Coupled with even small chemical anomalies (*e.g.* Bender, 1983; Maris *et al.,* 1984), the magnitude of ridge-flank discharge implies significant chemical exchange between sea water and basalt for some elements (*e.g.* Mg) and indicates that ridge-flank hydrothermal activity plays an important role in the chemical evolution of the crust and the ocean.

Heat flow data and fluid flow models suggest that ridge-flank circulation takes place in a wide variety of ridge-flank environments. These range from young crust drowned in terrigenous sediment, such as on the eastern flank of the Juan de Fuca Ridge, to sparsely sedimented ridge flanks in the central South Pacific and the western Pacific (*e.g.* Sayles and Jenkins, 1982 ; Becker and von Herzen, 1983 ; Mottl *et al.,* 1983 ; Maris *et al.,* 1984 ; Bender *et al.,* 1986 ; Kastner *et al.,* 1986). Although substantial progress has been made in characterising the thermal and chemical effects of hydrothermal processes at ridge crests, there is at present little except the large-scale pattern of heat flow to constrain general models of the ageing and chemical evolution of the crust and the

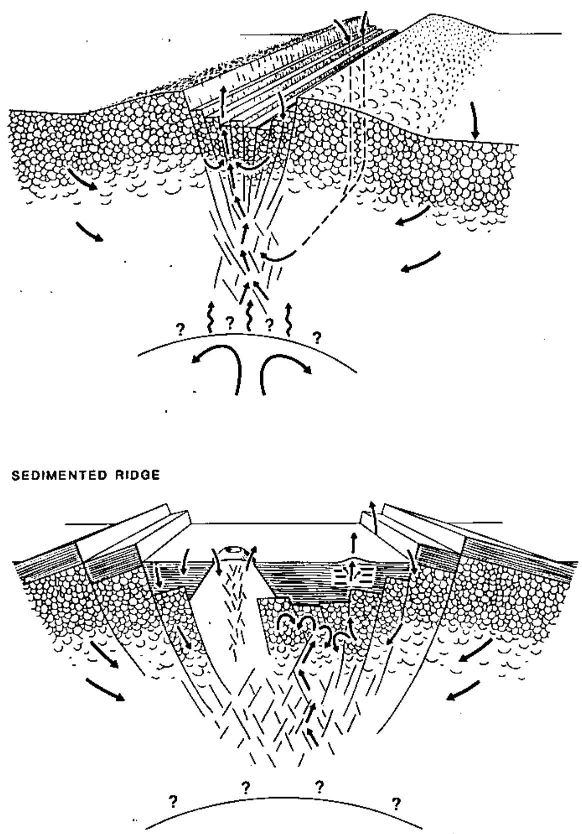

Figure 4. Schematic illustrations of hydrothermal circulation at sediment-free and sedimented ridges.

hydrothermal systems that alter the crust. Several important questions regarding the magnitude and chemistry of fluid discharge from ridge flanks, what controls its extent and where chemical exchanges cease, need to be addressed.

Most of the chemical information about ridge flank fluid circulation comes from work on basalt alteration in DSDP drill sites, especially in the Atlantic Ocean (*e.g.* Andrews, 1977; Donnelly *et al.,* 1979; Honnorez, 1981; Muehlenbachs and Clayton, 1976; Muehlenbachs, 1986; Thompson, 1983; and references therein). Information also comes from water chemical analyses, especially from the equatorial eastern Pacific region, in particular from the Galapagos Mounds area, and from the southern flank of the Costa Rica Rift (vicinity of DSDP Hole 504B) (*e.g.* Becker and Von Herzen, 1983; Mottl *et al.,* 1983; Maris *et al.,* 1984). Porewater studies from the Galapagos Mounds area suggest that ridge flank chemical exchange between sea water and oceanic crust may be an important component of the geochemical budgets of Mg^{++}, Ca^{++} and F^-. Porewater profiles in eastern equatorial Pacific ridge flank sediments suggest that ridge flank convection may be important for Ca^{++} fluxes into sea water (Sayles and Jenkins, 1982). The results from these few specific locations are, however, not easily translatable into global ridge flank chemical fluxes. In a synthesis of deep-sea sediment interstitial water concentration-depth profiles, McDuff (1981) has shown that a sediment column of approximately 300 m thickness usually serves to seal off the underlying basalts from convective communication with the overlying ocean. At greater sediment thicknesses, diffusive communication becomes the dominant mode of transport of major constituents of sea water. McDuff (1981) and Gieskes and Lawrence (1981) demonstrated that diffusive fluxes of Ca^{++} and Mg^{++} contribute insignificantly to the overall exchange flux between the ocean, the sediments, and the underlying basalt. But, as shown by Lawrence and Gieskes (1981), for oxygen isotopes even the diffusive exchange may be important. Hence, in younger sites with thinner sediment cover, which may show convective circulation, exchange fluxes for oxygen isotopes could possibly be very important. These few results suggest that the Ca^{++} and Mg^{++} fluxes resulting from moderate to low temperature reactions between sea water and MORB work in the same direction as those at high temperatures. The ^{18}O flux, however, works in opposite directions; at low to moderate temperatures (<200-250°C) MORB becomes enriched in ^{18}O, and at high temperatures it becomes depleted in ^{18}O.

In the Galapagos Mounds area, Fe is also significantly enriched in the hydrothermal Mounds field relative to pelagic sediments in low heat flow areas; the Fe-smectite nontronite is a major mineral in the Mounds. Similar to other dredged and drilled basalts, the Galapagos altered basalts are enriched in ^{18}O and ^{87}Sr. On the basis of chemical and isotopic analyses of the dredged and drilled altered basalts, the calculated amount of sea water which circulates and reacts with the basalt in the ridge flank regions is moderate to high (water/rock mass ratio >5-10), while in the ridge crest hydrothermal systems it is low (*e.g.* Thompson, 1983).

Most estimates of the magnitude of the off-axis hydrothermal element flux are heavily dependent on assumptions about the time at which crust is sealed to hydrothermal circulation (for thermal flux), and the time at which the crust is sealed to chemical exchange (for chemical flux). Neither of these parameters is well known. The chemical flux estimates for Mg and Ca are based on studies of the Galapagos Mounds hydrothermal system and assume that all chemical exchange ceases after 1.5-3 my. To illustrate the discrepancies in the currently available data one need only compare the evidence from the Sr isotopic composition of vein fillings in basalts drilled by DSDP which suggests that the flow of sea water through basalt largely ceases at crustal ages of 10-15 my (Hart and Staudigel, 1980), with the evidence from heat flow studies, which suggests that convection continues to affect surface heat flow for 30-80 my.

Further study of the chemical alteration of the crust through time combined with modelling holds promise of determining the magnitude and duration of the fluid flow. For example, crust less than 15 my old still contains a high proportion of Mg saponite, whereas crust of 15-50 my age contains more Fe-rich minerals such as nontronite and celadonite.

Heat flow surveys in the Galapagos Mounds and Costa Rica Rift areas (Becker and Von Herzen, 1983) suggest that fluid circulation takes place as free convection in cells that are in some cases regularly spaced and in other cases controlled by large-scale crustal structures like faults. The reasons for these differences are not fully understood, although it is thought that the permeability of the oceanic crust plays an important role. Thus it is necessary to know what determines the permeability of the crust and how it is reduced with time and in relation to the rate of sea floor spreading. Studies of DSDP cores suggest that changes in the circulation system are age-dependent. For example, the pattern of $\delta^{18}O$ variation with age is consistent with a model of extensive circulation of cold sea water for the first 10 my or so, after which circulation becomes restricted to locally permeable breccia horizons where it can continue for up to 25-50 my (Muehlenbachs, 1980). There are many other important aspects of the permeability structure that may affect ridge flank hydrothermal flux. For example, it may be that the permeability is great enough for convective cells to migrate through the crust so that they produce discharge surges when they merge. The permeability of the crust formed at slow-spreading ridges may be significantly different from that formed at fast-spreading ridges. It will take drilling combined with geophysical experiments to answer such questions.

Drilling Strategy

Because of the wide variety of environments in which fluid circulation takes place on ridge flanks and our lack of information about these environments, we believe that it is desirable to drill sites in several different environments. These should range from areas in which upflow zones are covered by rapidly accumulating terrigenous sediments, like the northern Juan de Fuca Ridge east flank, to areas in which upflow zones are covered by thin pelagic sediment blankets, like the southern tropical Pacific. Such sites should have been thoroughly surveyed prior to drilling with techniques such as multipenetration heat flow and porewater geochemical profiling, and with bathymetric and seismic imaging that will constrain the occurrence and field associations of the upflow zones.

The highest priority is for drilling in a relatively old system that will show the integrated effect of fluid circulation over a long period of time. Ideally this region should be experiencing fluid circulation, but should be closed to active (chemical) exchange with the crust.

To understand the nature and extent of deep crustal alteration taking place in the ocean flank environment it is necessary to drill a deep crustal hole. Such a hole would have to extend through the entire altered sequence of rocks. Based on ophiolite evidence, this would be approximately 3 km. In order to understand what portion of the alteration took place on and off axis, this hole should be paired with a deep crustal hole at the boundary between axis (forced) convection and flank (free) convection. Careful site surveys are required to avoid placing either hole in an area where there is a flank upflow zone. The deep hole should be combined with shallow holes in the vicinity, some of which should go as deep as the low permeability zone in the crust in order to address the possibility that the oceanic plate may not be as uniformly altered as suggested by the ophiolite data. This would allow the lateral mapping of permeability structure in the recharge area, and characterisation of a ridge-flank circulation cell in three dimensions.

Ocean Basins

The ocean basins are defined in this chapter as areas where pore-fluid convection has "apparently" ceased. In this zone large-scale major element chemical exchange between the ocean and the ocean crust is thought to be controlled principally by diffusion.

In the Basin Zone the oceanic crust is covered with a thick layer of sediments and heat flow measurements show very little or no spatial variation (*e.g.*, Anderson *et al.*, 1977, 1979 ; McDuff, 1981). The lack of heat flow variation suggests that convection has ceased, and that the thick low permeability sediment column provides a significant barrier to sea water ingress. Furthermore, Hart and Staudigel (1983) suggest from strontium isotopic composition of vein fillings in basalts drilled by the DSDP that the flow of sea water through basalt largely ceases at crustal ages of 10 to 15 my (see also Peterson *et al.*, 1986).

On the other hand there is evidence that the low-temperature chemical alteration of sediments near the base of the sediment column continues after large-scale warm-water convective exchange has ceased (Staudigel *et al.*, 1986). Also veins with alteration haloes have been observed in the sediment column, indicating that significant flow of fluids through the sediments has taken place after their deposition. Some of these are oxidation haloes suggesting the influx of sea water. Fluid circulation in the basins may be dominated by flow along fault zones and basement scarps. These features are not represented in studies such as those of Hart and Staudigel (1983). A few studies of sparsely spaced basement outcrops have shown that they are associated with locally more vigorous fluid outflow.

For these reasons it is not certain that fluid circulation has ceased to affect chemical transport over the extensive parts of the ocean that we have labelled the hydrologic zone Ocean Basin. Because of its large area, any fluid circulation in this zone could have some importance for the global chemical budget. One deep hole has already been proposed in the Basin Zone near the Flank Zone boundary to measure the total circulation that has occurred in the Ridge and Flank Zones (see the previous section of this chapter). Paragenetic and alteration studies of the deeper parts of this drill hole might contribute to the Basin Zone circulation question.

More surveys with heat flow and shallow sampling of pore fluid chemistry are necessary before any clear objectives for drilling in ocean basins to study fluid circulation can be formulated.

The diffusional processes operating in ocean sediments are influenced by changes in sedimentation and water chemistry. Consequently there is value in extending our knowledge of diffusional processes to deeper in the sediment column and consequently a longer record of these processes in time. This could be accomplished with HPC holes as part of other programs to investigate ocean basins.

HYDROGEOLOGY OF THE OCEAN MARGINS

Passive Margins

Hydrological pumps capable of circulating large amounts of water through the oceanic crust operate at continental margins. One important kind of pump is driven by continental rainfall. This rainfall raises the continental water table above sea level, producing flow into the oceans. Along margins that contain evaporites, this pump is often aided by negative buoyancy. The meteoric waters become saturated in salt, denser than sea water, sink to the lowest aquifers in the section, and seek to escape where those aquifers outcrop below sea level on the continental slopes.

Haline convection driven by dissolution of evaporites or by brines at continental margins could enhance dolomitization. Magnesium in sea water circulating into calcium carbonate sediments to replace denser-than-sea water solutions sinking and circulating out into the ocean at greater depth, or in magnesium-rich brines, could replace calcium in these carbonates. Such an exchange should be of major significance to the weathering cycle discussed in the Introduction, and could also significantly affect the permeability of the margin sediments.

It is also at the ocean margins that sediments accumulate to sufficient thicknesses to heat their organic constituents to the point where oil and gas are produced. These mobile organic phases are expelled (mostly ?) upward by buoyancy and compaction. They may be trapped as clathrates near the ocean interface or may react with sea water sulphate to produce H_2S. Other interesting phenomena occur at ocean margins, such as permeability-producing salt diapirism that in some cases locally restarts the convective circulation of sea water.

Recent work suggests that hydrologic flow from continents to oceans may be more important than has generally been appreciated. Infiltration to the Yucatan Peninsula appears to be eroding the carbonate edge of that peninsula by carbonate dissolution at a significant rate (hundreds of metres per thousand years in areas of focussed discharge). Carbonate dissolution occurs near discharge points since a mixture of calcite-saturated sea water and fresh water is undersaturated with calcite. The submarine discharge from the Yucatan Peninsula is about the same as that from the Potomac River (~10 km^3/yr). This recent work by Hanshaw and Back (1980) revives old suggestions by Johnson and Stetson in the 1930's that undersea discharge may erode valleys on the lower part of the continental shelf. Robb (1984) believes that "spring sapping" eroded submarine canyons off the New Jersey coast during the Pleistocene when sea levels were lower. He cites a variety of compelling observational and theoretical arguments in support of this hypothesis. The presence of a fossil Pleistocene fresh water plume extending 100 km off the New Jersey coast (revealed by the Atlantic Margin Coring Project of the U.S. Geological Survey; Hathaway *et al.,* 1979) supports Robb's suggestion.

Where organic material is encountered the fluids (even if cold) become alkaline and enriched in H_2S. The hypersaline seeps off the Florida escarpment, for example, are enriched in H_2S by bacterially mediated sulphate reduction. Large and stable vent communities are supported where these fluids discharge (Paull *et al.,* 1984). The Florida escarpment cold seeps appear, in fact, from a biological point of view to be more stable (long duration) than the hot seeps and discharges at the mid-ocean ridges. Although we do not know the magnitude of hydrologic flow into the oceans at the continental margins, it is clear that it is widespread, could be of large volume (comparable to the discharge at mid-ocean ridges), and it is often chemically quite different from sea water, so hydrologic discharge at ocean margins could be important to the global chemical balance of the oceans.

Another interesting recent development is the recognition that clathrate layers in the upper few hundred metres of sediments at more than 500 m ocean depth may be much more extensive than previously thought. These clathrates can be seen in seismic sections as a bottom-simulating reflector (BSR). Piston coring on the Gulf of Mexico slope demonstrates clathrates over a 25 600 km^2 area. Clathrates only form when gas concentration exceeds the solubility limits of the gases involved. Thus clathrate horizons mark areas where there is significant biogenic methane production or where there is migration of thermogenic gases from greater depths. Clathrates can store huge volumes of methane and act as a barrier to fluids. Their formation can also produce salinity and chlorinity maxima because sea water ions are excluded from the clathrate. The storage of huge volumes of gases as clathrates might be of economic interest if a way could be found to produce the resource.

Because the hydrologic flow from continents is potentially so volumetrically significant there is a great need to characterise it to find if it does contribute significantly to the ocean chemical budget. This would involve (i) the determination of the patterns of fluid circulation through continental margins and rates of lateral exchange with sea water. (ii) The diagenetic history of the edge of a continental margin as it relates to the patterns of fluid circulation. (iii) The nature of deposits formed by sea floor seepages, including sulphide mineralisation, chemosynthetically produced organic carbon layers, and the rich cementation of the sea floor with carbonate crusts from the oxidation of methane. Relatively little work is currently under way in these areas, although they are clearly of great potential importance. The most immediate need is probably for appropriate surveys of the various kinds of passive margin seeps, and some measurements of their chemistry, and discharge rate. Simple scoping models should be constructed to put the information obtained in a context where its implications for global chemical budgets can be assessed.

Drilling Strategy

Some drilling objectives can be identified and are appropriate. The COSOD II meeting did not rate these objectives as high priority, primarily because the need for prior surveys and theoretical studies seemed so great. In the near future drilling into the Florida escarpment to determine the mechanism of fluid flow to the cold, H_2S seeps, and to determine the chemistry of the seeps may be justified as having relatively high scientific priority. The driving mechanism is probably negative buoyancy due to the greater-than-sea water salinity of the brines. It could be driven by compaction of the Mississippi fan sediments or platform carbonates, however.

Over the next decade the feasibility of defining the permeability structure of a submarine fan should be seriously explored. The first stages of such an investigation would involve very detailed surveys. Such a project might eventually involve some drilling, however. For example, work on the Navy Fan off California by A. Bouma and others has shown that a very detailed picture of the internal plumbing system of a delta can be obtained when seismic sections and geophysical surveys are calibrated with drill core. If the present flow of fluids through such a well-documented submarine delta could be determined, a great deal would be revealed about hydrologic and chemical processes at passive continental margins. Large-scale fluid flow is probably best revealed by subtle surface heat flow variations. Thus a careful heat flow survey over the delta might be the best way to document the present fluid flow pattern.

Active Margins

Most of the hydrogeological processes acting at continental margins described in the previous section apply to subduction zones. There are, however, additional features that derive from their active tectonic situation.

That water flows out of the accretionary complexes formed at active margins is known from direct observation or by inference from the reduction in the porosity of the sedimentary rocks that form them (Von Huene and Lee, 1983; Bray and Karig, 1985; Kulm *et al.,* 1986). The patterns of flow of fluid out of complexes and the flow regimes within them are largely unknown. It is generally assumed that most of the water flow is from porewater expelled by progressive compaction in response to the increased load that is produced by the tectonic stresses that build an accretionary complex, either directly or indirectly by thickening the section above. Dehydration reactions and recirculation of sea water, however, may also contribute.

Dewatering is known to be pronounced at the toe of an accretionary complex, where sediments are rapidly deformed during accretion. Features such as mud volcanoes have been observed on the ocean floor in front of the complex, indicating the transmission of high pore-fluid pressures ahead of it (Westbrook and Smith, 1983; Breen *et al.,* 1986; ODP Leg 110 Scientific Party, 1987). Water escapes through a variety of features such as the thrust faults separating the anticlinal packets of accreted rocks, antithetic faults developed on the backs of the anticlines and vertical faults cutting across strike, or it may escape pervasively through the surface of permeable sediments (Fig. 5). Further landward in the accretionary wedge, long landward dipping thrusts that allow the wedge to maintain its equilibrium slope may also provide conduits for porewater to escape (Cloos, 1984). It is possible that dilatance and alteration of the rocks caused by water along these thrusts produces the acoustic impedance contrast that makes them visible. Faults appear to provide a network of fluid pathways within the complex. Permeable units within the accreted sediments, however, can be of equal or greater importance, especially where they extend over a large distance. Arenaceous rocks interbedded with clays assist the clays to dewater more efficiently. When clays cannot dewater easily they may produce mud diapirs which provide a mode of water expulsion that is episodic in its nature. By this means porewater moves with its matrix in a body through the overlying sequence to be released at or near the sea bed.

Models of the stress systems in accretionary wedges require high pore-fluid pressures at the basal decollement to reduce shear stress and some assume, but do not require, similarly high pressures throughout the wedge (Westbrook *et al.,* 1982; Davis *et al.,* 1983). The distribution of pore-fluid pressure in the wedge is largely unknown. We wish to know how pore-fluid pressures and flow respond to and influence the formation of individual structures. How do pressures change before, during, and after slip on the sub-wedge decollement or faults within the wedge ?

The sedimentary section that is initially subducted beneath an accretionary wedge is subject to an increased load from the weight of the wedge above it which will increase the pore-fluid pressure and tend to drive the porewater out. There is some evidence from ODP Leg 110 that water from these sediments may not easily escape through the wedge above. Thermogenic methane occurs only in the decollement and the sequence beneath it, but not in the wedge (ODP Leg 110 Scientific Party, 1987). It can be driven out laterally towards the toe of the complex and ahead of it. If permeable horizons exist within the section these will act as conduits. Also, the overpressuring could be great enough to cause hydrofracturing. Where this occurs along bedding planes it will predispose them to be detachment surfaces and it is probable that the basal decollement of the accretionary wedge may propagate ahead of the wedge by this means. Another possible route for porewater is through the permeable upper part of the igneous ocean crust. A balance will be achieved between the rate at which sediment is subducted and the rate at which water can migrate oceanward through it. One of the mechanisms by which fluids are transferred from the underlying sequence of sediments into the wedge is subcretion. Where this is shown on seismic sections it generally occurs by the formation of duplexes along the decollement. The deformation of the transferred "horse" of sediment encourages the escape of porewater from it through the wedge above. In the Barbados Ridge Complex, the onset of mud diapirism is roughly coincident with the onset of subcretion (Brown and Westbrook, 1987).

How deeply sediment is subducted and from what depth porewater from this sediment or water from dehydration reactions in the sediments or the igneous crust returns to the surface through the accretionary complex are very open questions. Water from the deeper part of the subduction zone may escape into the crystalline crust of the forearc and thence into the forearc basin. It may also act on rocks of the overlying mantle or ultramafic rocks within the crust to produce serpentinite diapirs such as those discovered in the forearc off the Mariana arc. The permeability structure of the crystalline forearc is very obscure. While it is likely to be dominated by fracture permeability there are no clear indications at the orientations of the fractures from current seismic and drilling data. Stresses in this part of the forearc are not so well understood as to make the prediction of their orientation straightforward. The serpentinite diapirs may act as channels. The water-rock interaction along fluid pathways could produce extensive alteration of the igneous component of the crystalline forearc.

Some water in the sediments and the ocean crust is subducted sufficiently deeply to play an important role in subduction zone magmatism. (This is a principal interest of Working Group 2). Several studies indicate that sediment is involved in magmatism, of which that by Tera *et al.* (1986) on ^{10}Be has indicated the short time taken for some elements to go through the system from ocean floor to eruption from an island-arc volcano. The budget for water within sediments depends *inter alia* upon the degree of accretion into the wedge, the permeability of the system and the rate of subduction. Rapidly subducted pelagic sediments at subduction zones where there is little or no accretion may contribute more water to subduction-zone magmatism than much thicker terrigneous sequences at systems with slow subduction rates and large accretionary complexes, because in the latter case most of the sediments are removed from the subducting crust and the water in the remaining attached sediments may be largely squeezed out. The influence of the accretionary complex on the dewatering of sediments in forearc basins is also a relatively unexplored issue. In the situation illustrated in Fig. 5, it would appear that the same mechanisms that are active at the front of the accretionary complex act on forearc basin sediments also, but where the forearc basin is separated from the accretionary complex by a landward dipping leaf of crystalline basement, the influence of the complex upon the basin sediments is unclear.

The composition of water flowing in accretionary complexes is often more dilute than sea water (Leg 110, Leg 112). This could be a consequence of one or more of the following :

(i) The action of clays as a semipermeable membrane filtering porewater, retaining salts on the high pressure side.
(ii) Dehydration of clay minerals.
(iii) Dehydration and/or recrystallisation of amorphous silica.
(iv) Decomposition of gas hydrates.

Many of the faults penetrated in Leg 110 contained water with a low chloride content. These low chloride anomalies indicate "active" flow, otherwise the anomalies would decay by diffusion in about 10^5 years. Flow was also shown by temperature profiles that indicated advective heat transport.

In the area of the Barbados Ridge Complex investigated by Leg 110, gas hydrate does not appear to be present, but elsewhere in accretionary complexes it is widespread. Gas hydrates are potential barriers to the flow of fluids out of accretionary wedges and where they are present they must restrict outflow to fissures, predominantly faults, along which the flow of warm water prevents hydrates from forming.

Meteoric groundwater driven by the gravitational head provided by the elevation of the island arc or continental margin or evaporitic brines may be important components of water in forearc basins. The results of Leg 112 and studies of the water budget of basins onshore show that this occurs off Peru.

To advance our knowledge of the flow regime of accretionary complexes, we need to discover the distribution and rate of water outflow. This can be addressed most effectively using measurements of heat flow, porewater pressure and possibly electrical potential, combined with high resolution seismic reflection, side-scan sonar, photography and direct observation to identify features associated with water outflow. By drilling we can make direct measurements of porewater pressure, the thermal structure, permeability, and porewater chemistry. From examination of core samples in relation to downhole measurements and seismic sections the influence of structure and lithology on controlling fluid pathways can be assessed. Suitable instrumentation emplaced in drill holes would allow the investigation of the relationships between strain and pore-fluid pressure and flow over a period of time.

Drilling Strategy

To establish the water flux, its routes, relation to tectonics and chemical transport, at least one deep hole is required in any one system to penetrate through the accretionary wedge, the underlying sediment layer and into oceanic igneous basement, to give one complete vertical transect and investigate the possibility of fluid flow in the igneous basement. In addition an array of shallower holes are needed to map the horizontal variations and to investigate particular elements of the forearc system. A deep hole may be of up to 4 km penetration to enable study of an accretionary wedge system at a significant distance landward of its toe where out-of-sequence thrusts and subcretion ramps are developed and thermal effects are becoming important, but still in a region where structures are imaged clearly by seismic reflection. The array of shallower holes, with an average penetration of 1100 m, would address :

(i) The extent to which fluids are driven outward into the ocean

floor sediments and uppermost igneous crust on the subducting plate.
(ii) The role of faults as fluid conduits and their periods of activity as such.
(iii) Flow paths within individual thrust slices.
(iv) The distribution of overpressuring in the accretionary wedge and beneath it.
(v) The effect of water outflow on the sediment drape covering the wedge.
(vi) The extent of water flow into the forearc basin from the accretionary wedge and from the adjacent arc or continental margin.
(vii) The flow of water through the crystalline crust of the forearc. This would in the first instance be oriented to drilling obvious features such as serpentinite diapirs.
(viii) The chemical evolution of the fluids within the accretionary wedge and the chemical flux into the ocean.

Several of these holes, including the deep one, should be instrumented and continuously monitored with pressure sensors, strainmeters and seismometers to study the relationship between strain, seismic slip and porewater pressures. Overpressured formations are likely to produce problems for drilling, and drilling mud will probably be required to control hole stability.

The thorough investigation of one system is of the highest priority, but an exploration of dependence upon major variables such as subduction rate, sediment thickness and sediment type is necessary. Consequently, studies should be made of systems that are sediment-starved (with only pelagic sediments), dominated by fine-grained sediments, and dominated by coarse-grained sediments.

TECHNOLOGY TO ADDRESS HYDROGEOLOGICAL PROBLEMS

The diagnostic parameters of active hydrogeological systems, whether they are thermally, gravitationally or tectonically driven, are sub-bottom temperature, pressure and

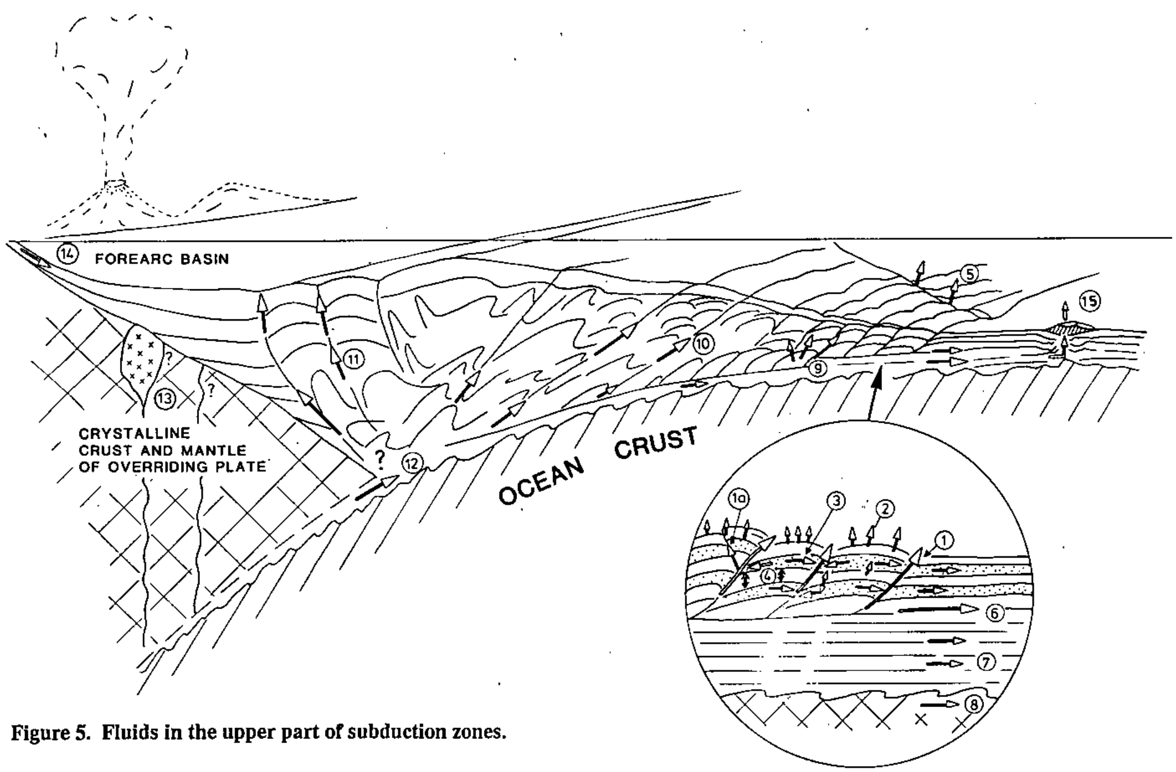

Figure 5. Fluids in the upper part of subduction zones.

1. Fluid escape along thrust fault associated with accretion at the front of the wedge, and (1a) along faults antithetic to these.

2. Diffuse flow out of the sea bed in response to compression. Fractures produced by local tensile stress at crest of anticlines may aid outflow.

3. Lateral flow along more permeable units in accreted sequence, feeding flow through faults.

4. Flow from less permeable units into more permeable units.

5. Outflow from vertical strike slip faults intersecting the accretionary wedge.

6. Horizontal flow along the decollement beneath the wedge.

7. Outward flow in sequence beneath wedge in response to the load of the wedge.

8. Flow in permeable upper part of oceanic igneous crust (?)

9. Release of water into the wedge as a consequence of the deformation of subcreted (underplated) packets of sediment in duplexes.

10. Flow along major out-of-sequence landward dipping thrust that enable the wedge to maintain its critical taper. Local dilation and vein deposits from outflowing water may be the cause of the acoustic impedance contrast that gives these faults seismic visibility.

11. Flow along backthrusts into the forearc basin.

12. Upflow from deeper parts of the subduction zone of water released by dehydration reactions. This will be dependent to some degree on subduction rate.

13. Water from deeper part of subduction zone penetrating fractures in overriding lithosphere. Fractures are probably radial to the island arc. Hydration of ultramafic rock may cause formation of serpentinite diapirs.

14. Meteoric groundwater from island arc or cordilleran continental margin seeping into horizons in the forearc basin, and then into basin.

15. Outflow through mud volcano on ocean floor in front of wedge.

flow regimes. To characterize a hydrogeological system it is critical to know the *in situ* physical properties of the host materials; their geometries and structural associations; the chemistry of interstitial fluids and gases; the petrography and alteration state of host rocks; and the tectonic and regional associations of the hydrological system.

Penetration into the sea floor by drilling offers the opportunity to measure directly many of these parameters and obtain the relevant samples. However, the objective of obtaining reliable and representative measurements indicative of sub-sea floor fluid movements is often difficult and requires carefully designed experiments and techniques.

Downhole Measurements

Much of the data relevant to hydrogeological systems is obtained by downhole measurements or experiments, which fall into three main categories.

1. Experiments that measure profiles of physical properties, chemistry or drill hole characteristics (well logging).
2. Long-baseline experiments that measure properties averaged over large volumes of sub-bottom rock.
3. Instruments installed in deep-sea boreholes to make long-term measurements of *in situ* parameters and properties.

Well Logging

Many standard logging tools such as sonic, resistivity or neutron density tools give indications of porosity, permeability and density - essential parameters for characterizing hydrogeological systems. These tools continue to improve within logging industry, and ODP's current contract with Schlumberger Inc. has made many of the most recent developments available to the Ocean Drilling Program. The tools now in use on the *JOIDES Resolution* are described in the "Wireline Logging Manual" available through the Borehole Research Group of Lamont-Doherty Geological Observatory. Below a few logging tools that deserve special attention relative to hydrogeological studies are described.

a. The multi-channel sonic tool that allows full waveform analysis. Data from the MCS tool provide the velocities of compressional, shear and Stoneley waves to be determined accurately.

b. Very high resolution resistivity tool (Formation Microscanner), which provides a continuous resistivity image of the entire hole wall. It maps porosity structures, fractures and veins with a resolution that rivals visual inspection of cores retrieved from the hole. The Formation Microscanner is a powerful tool for use in sedimentary sections where the borehole televiewer usually gives poor results.

c. The borehole televiewer instrument provides critical information on the extent and orientation of fractures, contacts, and hole geometry. This tool also can provide an indication of the direction of maximum horizontal stress. The televiewer finds its best application in consolidated sedimentary rock and igneous basement rocks.

d. A tool string made up of an "Induced Gamma-ray Spectroscopy Tool", a "Natural Gamma-ray Tool", and a modified Natural Gamma-ray Tool provides elemental abundances of Ca, Cl, Fe, H, S, K, U, Th, Al, Gd, and Mn. This chemical analyser has proven to be an excellent mapper of altered zones, vein fillings and porosity.

All of the high resolution imaging tools would benefit from complete stabilization of the tool in the hole during hoisting to prevent smearing of high-resolution images.

Packers

Truly representative samples of interstitial fluids and gases have proven very difficult to get in semiconsolidated and consolidated sediments and basement rocks. The principal problem is that sea water circulated in the hole under pressure replaces much of the original interstitial fluids in the wall rocks during drilling. As a consequence existing packer tools, which seal off a section of hole and draw in fluids from the walls by suction, usually acquire fluids that are highly diluted by sea water. A new wireline packer is scheduled to get its first tests this year (1987) and may provide a solution. This packer is lowered through the drill string in the same manner as a logging tool to the interval to be sampled and twin elements are inflated to seal off the annulus between the tool and the whole wall. Pumps in the tool are activated to draw water from wall rock in the packed-off interval. Sensors can be placed in the plumbing to detect when true formation water is being collected. The use of packers to sample formation fluids and to make other types of measurements must get much wider use in the ODP program than they currently receive and the use of a multiple packer capable of simultaneously isolating several intervals would be very beneficial.

Measurements in High Temperature Holes

The 350 to 400°C water issuing from black smokers on the ridge axis indicates that very high temperatures will be encountered at shallow sub-bottom depths if ODP drills into discharge zones on zero-age crust. High temperatures will also be encountered in very deep holes into young (<50 Ma) oceanic crust. High temperatures present formidable problems for drilling, sampling and downhole measurements. For hydrogeological studies the important tools to be developed for high temperature holes are recording thermometers, flow meters and sampling devices. Some tools that can operate at temperatures up to 400°C for a short time (hours) have been developed by the Japanese. These tools are necessarily simple in design. A suite of proven high-temperature logging tools, samplers and high-temperature cable (one of the major problems) should be part of the inventory on future drilling platforms.

Long-Baseline Experiments

Several seismic and resistivity experiments have been carried out in deep-sea drill holes that use the full depth of the hole to image a large volume of material. These experiments provide an image of the broader structure of the crust, which is critical since there is evidence that the flow of water in the crust may be controlled by large-scale fractures that may not be intersected by the drill hole.

Vertical Seismic Profiling (VSP) and Oblique Seismic Experiments (OSE) have been successfully carried out in DSDP and ODP boreholes. VSP experiments provide a detailed velocity depth profile along the hole and a high-resolution reflection seismogram for the drill site. The OSE is a wide-angle refraction experiment that gives a detailed look at the velocity structure of the crust at the scale of hundreds of meters.

A new experiment for certain hydrogeological studies is an oblique shear-wave experiment in a deep sedimentary hole to measure the S-wave velocity profile. This experiment can be used to deduce geotechnical properties, detect overpressured zones in the crust and determine the effective stress as a function of depth in the sediments. The experiment would be particularly valuable in the accretionary prism environment where overpressured pore-fluids are known to exist and the effective stress in the actively deforming wedge is small.

Long-baseline resistivity experiments have also been carried out in basement holes with success. These experiments measure the large-scale resistivity of the crust which can be directly related to porosity and at deeper depths temperature. Electromagnetic sounding techniques can also take advantage of the geometry of a deep basement hole to image the resistivity structure deep in the crust.

Future seismic and resistivity techniques might utilize tomographic techniques between holes to image the heterogeneous velocity structure of the igneous crust. This would require drilling a few relatively deep holes (500 m into the crust) a few kilometres apart.

Long-Term Experiments

Permanent installation of thermometers and pressure gauges in boreholes offers an opportunity to monitor the borehole's return to equilibrium and determine accurate heat flows and pressure fields. At the time of drilling there are problems in making such measurements that result from the fact that forced circulation during the drilling operation disturbs the pressure and temperature, alters *in situ* properties, and contaminates samples. In some cases such as at DSDP Site 395, the opening of a hole through the low-permeability sedimentary layer has permanently changed the hydrogeological environment. Consequently, it is necessary to reseal some of the holes to arrest vertical flow in the hole and prevent the free exchange of sea water between basement and the ocean or exchange between other aquifers, and follow the return to equilibrium.

Placing an array of sensors for temperature, flow and pressure in a resealed hole that is multiply packed or backfilled can provide a long-term experiment that would allow the permeability and storage capacity of large volumes of material around the hole to be calculated. It would also provide an accurate determination of temperature and pressure profiles in holes as well as geothermal heat flux. The instruments installed in a hole should include a means to sample water and gases without violating the seal.

Long-term monitoring requires repeated visits to sites to make measurements or to collect and replace recorders on the sea bed or in the tops of the holes. Alternatively, instrumentation at a hole or close group of holes might be monitored via acoustic telemetry to a surface buoy and thence via satellite link to a land-based data centre. Even so, periodic visits by a ship would be required to maintain the integrity of the buoy and its mooring and to renew power sources for the instruments.

Sampling Techniques

Rocks and Sediments

The hydraulic piston corer (HPC) and extended core barrel (XCB) were introduced during the drilling program and have greatly increased the recovery in sedimentary sections of the oceanic crust and greatly decreased the mechanical disturbance resulting from coring. Complete and mechanically undisturbed samples are essential to characterizing the physical properties of the sedimentary section. However, it is still very difficult to get complete recovery and undisturbed samples of semiconsolidated and consolidated sediments and igneous rocks, especially when unconsolidated or semiconsolidated material, such as alteration products, alternates with igneous rock.

Drilling ahead of the Bit

The capability to drill ahead of the main bit with a small diameter narrow-kerf rotary coring bit promises one solution to this problem. The NAVIDRILL, now being tested by ODP-TAMU, will have this capability, and should provide more complete and representative samples with much less mechanical disturbance of the cored material than the current rotary coring techniques. Samples obtained by the NAVIDRILL should give a clearer indication of the small-scale fracturing, vein filling and alteration. It would also provide excellent specimens for measurements of hydraulic and geotechnical properties.

The "Probe Hole"

The NAVIDRILL capability also provides a true to gauge hole in which experiments and measurements can be made more accurately and reliably. The clean hole made by the NAVIDRILL or similar technology can be utilized to make more reliable and precise measurements of parameters in semiconsolidated and consolidated rock, such as porosity, permeability, density, conductivity and shear strength.

The hole created ahead of the bit may be up to 10 m deep and will be much less disturbed thermally and chemically than the main drill hole. Because of the short duration of the disturbance it will also dissipate quickly. This will allow representative fluid samples to be drawn using a packer, as well as temperature gradient and pressure measurements. The "probe hole" concept offers one of the few ways of accurately making critical hydrogeological measurements in semiconsolidated and consolidated strata. Use of the hole created by the NAVIDRILL for hydrogeological measurements is recommended by a recent workshop on physical properties (report by D.E. Karig and M.H. Salisbury, 1987, available through JOI Inc., Washington, DC).

Non-Drill Ship Re-Entry of Existing Boreholes

Much of what we now know about the hydrogeology of the ocean crust was learned by re-entering boreholes long after they were drilled. The long-baseline experiments and long-term experiments outlined above will also require many re-entries of current and future drill holes. There would be great gains in terms of cost and logistics if re-entry of boreholes could be achieved from a conventional research ship of moderate size. In addition non-drill ship re-entry would allow current and future sophisticated logging technologies to be used in existing boreholes.

Non-drill ship re-entry is currently feasible due to the existence of precise ship and bottom navigation, dynamic ship positioning and near-bottom imaging of the sea floor, and self-contained manoeuvring units on bottom vehicles. Development of a non-drill ship re-entry capability would enhance the use of boreholes for hydrogeological investigations.

SURVEYS

Drilling the oceanic crust and sedimentary sections is the only way to obtain reliable information about the conditions at depth where fluids circulate and chemically exchange solutes with the host formation. Proper characterization of the fluid flow system in plan is just as important, however, and it is critical to accomplish this in advance of any drilling. By doing so, holes can be optimally positioned and information gained while drilling can be properly placed in the context of the setting. One of the most important considerations for any site survey observations is scale. The permeability structure of sediments and of the oceanic crust is highly anisotropic, and as a result, flow systems may be horizontally highly exaggerated. A good example of this is seen in the case of off-axis hydrothermal circulation within sediment-"sealed" oceanic crust. Pore-fluid convection appears to occur with "cell" dimensions of 5-10 km (*e.g.* Williams *et al.,* 1974 ; Davis *et al.,* 1979) in a medium where the greatest permeability occurs in the upper hundreds of meters of crust (Hickman *et al.,* 1984 ; Anderson *et al.,* 1985). Even more extreme is the scale over which heat is advectively transported through the oceanic crust to discrete basement outcrops (c. 20 km) (Sclater *et al.,* 1976 ; Davis, 1987). Similar scales of horizontal fluid transport are probably involved in most sediment-hosted fluid-flow systems as well, with evidence from the accretionary prism off Barbados (ODP Leg 110 Scientific Party, 1987) and the passive continental margin off Mexico (Hanshaw and Back, 1980) providing good examples. Hence, to be most useful, site survey information must be extensive enough that the full scale of the hydrologic system into which drilling will penetrate can be fully observed. At the same time observations are required to be sufficiently detailed to characterize, without aliasing, the pattern of fluid circulation in plan, any relevant geologic structures, and the structure into which drilling will penetrate. Having sufficiently detailed information, comparisons of bulk-rock properties estimated from survey data to properties determined locally in the borehole can then be made. A combination of detailed bathymetry, acoustic imagery, seismic reflection, seismic refraction, electrical resistivity, heat flow, and geochemical gradient studies can provide information about bulk physical properties as well as about the regional hydrogeologic regime, for example the topography of the "permeable" basement/"impermeable" sediment cover contact, the sediment thickness, the geometry of potentially permeable (or impermeable) units within sediment sections, the location of any permeable paths to the surface, the locations and geometries of faults, the temperatures and porosities of permeable formations, the extent, depth, and shape of heat sources (magma chambers or unfractured hot-rock units), and the locations of fluid discharge and recharge. Effort also must be made to provide thermal and chemical constraints on the degree of exchange between sea water and the sediments or crust by observing fluids and precipitates at sites of discharge. In this way, models for predicting "end-member" fluid composition from mixed discharge-fluid compositions can be tested, once deep fluids are sampled by drilling.

Good site characterization may require the application of novel methods and technologies as well as those more traditionally used. Determining the rate of fluid flow through unconsolidated sediments can now be accomplished using measurements of permeability and *in situ* pore pressure (Schultheiss and McPhail, 1986); with minor improvements, this determination could become rapid, routine, and usefully applied in sedimented ridge axis, ridge flank, basin, and active margin environments. A technique for estimating fluid flux through exposed basement would be extremely valuable in sediment-free ridge axis environments. Incorporating onshore hydrologic studies with those done offshore in passive margin environments will be critical.

Site surveys can provide a good snapshot of fluid-transport processes, but in the most vigorous systems, namely those at mid-ocean ridges, the systems may evolve rapidly enough to warrant long-term monitoring experiments, not only downhole, but also at the surface. In those cases, careful thought must be given to integrating post-drilling experiments with long-term systematic observations made at the sea floor with the goal of understanding the temporal behaviour of, and interrelationships between, volcanic, tectonic, and hydrothermal processes.

In summary, high-quality and extensive site survey information is absolutely critical to the success of solving problems related to fluid-rock systems through ocean floor drilling. This is true perhaps to a greater extent than it is for any other class of drilling objectives. This will require levels of effort significantly greater than those given to pre- and post-drilling studies in the past. Fewer sites will be visited, but the level of understanding gained about fluid-crust interaction will be greatly enhanced.

RECOMMENDATIONS AND IMPLICATIONS FOR THE OCEAN DRILLING PROGRAM

Workshop 3 at COSOD II was scientifically stimulating for its participants, for while it revealed how little is really known about one of the Earth's major processes, it gave exciting glimpses of what might be achieved, and it brought into focus those elements of the fluid circulation system in ocean lithosphere that should yield most to potentially powerful multidisciplinary modes of investigation based upon drilling. Progress requires technological developments, and a summary of the most critical ones is given below.

Critical New Technologies for Future Hydrogeological Investigations using Deep Sea Drilling

Drilling and Coring Technology

1. *Stabilization of re-entry holes in unstable sedimentary sections:* A means to keep holes open for deepening and downhole measurements is urgently needed for hydrological investigation in accretionary complexes, and other unstable sedimentary sections.

2. *High temperature drilling technology:* Drilling into a discharge zone on the ridge axis will encounter rocks and fluids at 400°C and higher at shallow depths. Scientific goals identified in this chapter could involve penetrating and coring rock at temperatures up to 800°C.

3. *Ultra-deep drilling capability:* Holes 2 to 3 km deep are required to reach the "heat collector zone" or the bottom of a recharge limb of a crustal convective cell. In the recharge zone additional problems related to highly fractured hard basalt will be encountered.

Sampling and Measurement Techniques

1. *Development of better hole isolation techniques:* Extraction of representative formation fluids, measurements of pressure and *in situ* stress require isolation of intervals of the hole. Packer techniques used during DSDP and ODP are still unreliable and inadequate for some objectives. A vigorous and innovative approach to packer technology for use on the drill ship and for long-term isolation experiments is required.

2. *Narrow-kerf drilling ahead of the drill bit and instrumenting the small-diameter true-to-gauge hole produced:* This is one of the most important future developments for future hydrogeological work, and should be given high priority.

3. *Non-drill ship re-entry of deep-sea boreholes:* Many of the long-baseline experiments, hole-to-hole experiments and long-term observatories will only be practical if a capability to re-enter existing deep-sea drill holes (without and with bridges) using a large conventional research vessel is available.

Surveying Techniques

1. *Techniques to measure flux through unsedimented seafloor:* Measurements of sea floor heat and fluid flux in areas where there is no sediment are essential to map hydrothermal circulation in the vicinity of most ridge axes. With accurate maps of flux drilling targets can be optimally located for the best conditions.

Priorities and Outline Strategy for Drilling

During the Workshop a general approach to the investigation of each hydrodynamic zone was reached during discussion. These approaches are described in the sections on drilling strategy above. A poll of participants was conducted to assist in establishing priorities. The two zones considered to warrant most attention are active margins and mid-ocean ridge axes: the former, because of the crucial role played by pore fluids in controlling the dynamics of accretionary complexes, their importance to island-arc volcanism at the end of the cycle of oceanic lithosphere, and because active margins are the only zone where there is a net loss of fluid from the crust to the ocean; the latter, because it is at mid-ocean ridge axes that the most vigorous high-temperature hydrothermal systems occur and that water is first introduced into new crust. Mid-ocean ridge flanks were placed next in priority. Being the zone with the largest total fluid flux, they are of major significance to the global geochemical budget but, to evaluate them properly, it is necessary to know the effects upon the crust produced first by the mid-ocean ridge axis hydrothermal system. Passive margins have over recent years shown to be host to major fluid circulation systems of great diversity that could have a profound influence on diagenesis and the global geochemical budget. The present knowledge of these continental margin systems, however, is not sufficiently well developed to be able to propose any drilling proposals except perhaps for saline seeps from carbonate margins. More surveys and theoretical studies of continental margins are required. There is also more to be learned about diffusional processes in ocean basins. The HPC should be used to extend deeper present information derived from piston cores. A special program is not proposed for this, but studies of diffusional processes should be incorporated into other programs that site holes in ocean basins. A summary of estimated times for drilling to accomplish hydrogeological objectives in the four major areas is given below.

Estimated Drilling Times for the Programmes Suggested by Workshop 3

ACTIVE MARGIN

	Water Depth (m)	Penetration (m)	Days to TD	Logging and Experiments
Deep Hole	5000	<4000	<76	30
6 Shallow Holes	5000	1100 (Ave)	19 (x 6)	8 (x 6)
		Total	190 +	78
			= ***268 days***	

Repeated 3 times for starved pelagic, fine terrigenous sediment and coarse sediment margins = ***804 days***.

MID-OCEAN RIDGE AXIS

	Water Depth (m)	Penetration (m)	Days to TD	Logging and Experiments
2 Deep Holes	3000	3000	90 (x 2)	25 (x 2)
4 Shallow Holes	3000	700 (Ave)	21 (x 4)	5 (x 4)
		Total	264 +	70
			= ***343 days***	

Repeated 2 times for bare and sedimented ridges = ***686 days***.

MID-OCEAN RIDGE FLANK

	Water Depth (m)	Penetration (m)	Days to TD	Logging and Experiments
Deep Hole	4000	>3000	>90	25
4 Shallow Holes	4000	700 (Ave)	21 (x 4)	5 (x 4)
		Total	174 +	45
			= ***219 days***	

Repeated 3 times for different environments of sedimentation and spreading rates = ***657 days***.

PASSIVE MARGINS

	Water Depth (m)	Penetration (m)	Days to TD	Logging and Experiments
Two Holes	3000-4000	1500	26 (x 2)	10 (x 2)
		Total	52 +	20
			= ***72 days***.	

All drilling time estimates are based upon the projections for a slimline riser system prepared by Frank Schuh and other members of TEDCOM for COSOD II. Estimates for the shallow holes in the active margins also take into account the drilling times for ODP Legs 110 and 112.

If all these programs were to be carried out fully (allowing 40 days in 60 for drilling), they would require 9 years 2 months to complete. If, however, a minimum program of single examples of the two highest priority regions (active margins and ridge axes) plus one deep hole in a ridge flank were undertaken, then only 3 years would be needed. Several of these holes could also meet the objectives of other programs. Seen in this light, the minimum program makes a modest demand upon the time available to the Ocean Drilling Program over 10 years.

The priority of individual elements of a drilling program is strongly dependent upon technological developments. Consequently, while it is considered by many that a deep hole in a bare mid-ocean ridge axis is probably the single most important hole for understanding ridge-axis hydrogeology, it is recognised that in the early part of the program the technology to drill such a hole effectively will not be available and that more would be gained scientifically by drilling shallow holes in a sedimented ridge or in other zones such as active margins. The involvement per hole in time and scientific attention will increase and a corresponding increased investment in site surveys will be needed to optimise the siting of holes and understanding of the information gained from drilling in the context of its geological setting. The development of techniques and results from the early part of a program would undoubtedly lead to changes in the design of drilling legs and short-term priorities, but these should not divert ODP from pursuing its long-term scientific objectives. It is important that all the first order hydrogeological processes of the ocean crust which form a cycle be investigated. A well-paced program, in which the drilling and sampling technology are advanced while maintaining scientific momentum, is required. The Ocean Drilling Program will need to sustain this and other thematic programs over a decade to provide a climate of confidence in which major scientific and technological investment can be made. Changes may be required in the planning mechanism of ODP to accomplish this, but they would be well justified to gain the reward of understanding the interaction between the Earth's oceans and crust.

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Stress and Deformation of the Lithosphere

Prepared by WORKING GROUP 4 (see p. 10)

ABSTRACT

Plate tectonics has led to a basic understanding of the kinematics of the lithosphere ; knowledge of the stresses acting on the plates will lead to an understanding of the dynamics of the lithosphere. Theoretical models have been constructed assessing the importance of ridge-push, trench-pull, plate-drag, etc. Data of the stresses within the plates and at their edges would permit distinguishing between these models. Stress measurements on continents in the last decade have shown that there are large regions of uniform stress orientation (*e.g.* the direction of maximum horizontal compressive stress throughout most of eastern North America is oriented NE-SW). Recent work with televiewer observations of borehole breakouts made aboard the *JOIDES Resolution* has shown that these same measurements can be made at sea. We propose that measurements of the stress within the oceanic plates be made globally, about 1000 km apart. There should be local tectonic influences to the regional patterns near plate boundaries, and we propose several studies of stress patterns near deep sea trenches, transform faults and spreading centers to test existing models of these environments. These measurements combined with the determination of stress on land and derived by earthquake focal mechanism solutions will lead to an understanding of the forces driving the plates.

"Seismic tomography" made by the global network of digital seismic stations is showing large regional variations in the seismic velocity of the upper and lower mantle. From these velocity anomalies, the positions of hot rising and cold sinking regions of the mantle are being mapped for the first time. Stations in the ocean basins are needed to complete the global picture. The Global Seismic Network program aims to solve the mantle heterogeneity problem in the next decade. A minimum of eleven stations on the seafloor are needed to complete this study at the desired resolution. We propose establishing these down-hole laboratories to further understand the mantle beneath the plates and the convection currents that drive the plates.

Finally, we have identified objectives at the margins of oceanic plates. We wish to understand the processes that are responsible for the tectonic development of the rifted edges of passive margins. The sediments and underlying crystalline rocks of the passive margins contain the information needed to understand the thermal and structural evolution of this tectonic domain. Direct drilling to reach these objectives is beyond the present drilling capabilities, but aspects of magmatic processes and how continental crust responds to stretching and loading during rifting can be studied at selected sites. Furthermore, we wish to further our understanding of the processes responsible for the spectrum of deformation associated along the toe of a convergent forearc by measuring stresses, porosity and pore pressure variations, deformation structures, etc., and measure these same properties in the "decollement" between the forearc and the plate below.

GENERAL SCIENTIFIC OUTLINE

In response to recommendations from the COSOD II Steering Committee, the focus of this Working Group "Stress and Deformation of the Lithosphere" is to address the general aspects of the mechanical and dynamic behavior of oceanic lithosphere.

Oceanic lithosphere is an evolving medium that changes substantially with increasing age and, in this sense, it is living. Oceanic lithosphere is born along the axes of the world-encircling mid-oceanic ridge system. Magma, derived by partial melting in convecting limbs beneath the ridge, is episodically emplaced in shallow reservoirs where it crystallizes to create oceanic crust, the uppermost component of oceanic lithosphere. The underlying component is composed of residual mantle peridotites depleted by partial melting. As oceanic lithosphere moves away from the axis of the ridge, the aging process continues as the lithosphere thickens by conductive cooling, becoming increasingly stronger. The properties of the oceanic lithosphere are modified further by hydrothermal alteration of its crustal skin, by disruption of its lateral continuity as a result of faulting, and by off-ridge magmatic events which thicken and load the lithosphere. Oceanic lithosphere is lost or re-cycled along convergent plate boundaries at subduction zones, where lithosphere of variable age is thrust into the upper mantle beneath an overriding orogenic belt. At depth, the oceanic lithosphere is progressively consumed by conductive heating and incorporated into the convecting mantle.

The stress and deformation history of oceanic lithosphere can only be understood if investigations and experiments are carried out within all the major tectonic domains of the oceanic lithosphere : rifted continental margins, the mid-ocean ridge system, intraplate and subduction environments. The geologic properties of each one of these tectonic domains are the product of a range of igneous, metamorphic, sedimentologic and structural processes that create, in time and space, a characteristic assemblage. Another very important aspect of stress and deformation of the lithosphere is a definition of the processes that characterize the creation of an ocean when continental lithosphere is stretched and rifted apart.

In order to unravel the geologic complexities of each tectonic domain, an integrated investigative approach must be developed that will involve a range of high resolution tools (*i.e.* multichannel seismic-reflection and seismic-refraction profiling, side-scan sonar and bathymetric swath mapping, and submersible and deep-earth sampling). The combined results will provide complementary constraints on the properties of a given environment. Ideally, remote sensing and indirect sampling investigations would first be carried out at a regional scale, defining the tectonic framework into which site-specific surveys would then be placed. These data would be used in turn to locate a hole or a series of holes that would serve as probes into the tectonic domain of interest. The drill bit provides important data on the vertical constitution of the upper portions of the lithosphere by recovering samples, and the drill hole serves as a conduit into the lithosphere making it possible to carry out a suite of *in situ* measurements that are critical to the definition of the tectonic processes which have shaped and are shaping the lithosphere. Holes that are located in key geologic settings will be used as long-term physical-chemical observatories that will monitor the tectonic pulse rate of the environment in question. The importance of this approach was outlined in the COSOD I document, but recent technological developments in downhole instrumentation now make it possible to carry out a wider range of sophisticated measurements and experiments.

In terms of the stress and deformation of the lithosphere, we believe that it is fundamental to establish the strain and kinematic history of the major deforming oceanic plate boundaries (mid-oceanic ridge system, convergent margins, rifted margins) and the state of stress within oceanic lithosphere, including a global sampling of plates, their interiors and margins. As a component of the state of stress program, some of the holes that are located in the interiors of large plates, far from the seismically contaminating effects of anomalous lithosphere (*i.e.*, continental lithosphere, island arc orogenic belts, intraplate volcanic edifices), should be used as seismic stations, and be part of the Global Seismic Network. The seismic data obtained at these stations will greatly improve the capability for tomographic imaging of the interior of the Earth. These imaging data, in turn, provide exciting, new and fundamental insights into the causative processes that shape the Earth's surface.

The drilling program that we envision is a phased program in that there are certain facets that can be initiated almost immediately, because the drilling and down-hole instrumentation technology is ready and the scientific problems to be addressed are mature. Other facets of the program cannot be implemented for some time, because drilling technology has first to make some needed advances in penetration and recovery rates, and because the scientific problems are not as yet mature.

In this sense, our highest and immediate objective is the global determination of the state of stress and physico-chemical properties of oceanic lithosphere. This program would represent a commitment to establish the state of stress in a range of tectonic environments within oceanic plate interiors as well as at the margins. The establishment of ocean bottom geophysical observatories at a few sites would be part of this program.

On the other hand a high-priority objective that requires a long-term commitment is to understand the processes that are responsible for the tectonic development of the rifted edges of passive margins. The sediments and underlying crystalline rocks of the passive margins contain the information needed to understand the thermal and structural evolution of this tectonic domain. In addition to learning how this potentially oil-rich sedimentary assemblage evolves, we will learn how mechanical deformation and thermal evolution of the lithosphere interact with magmatic processes and how continental crust responds to stretching and loading during rifting.

Another important objective is to understand the processes responsible for the spectrum of deformation associated with plate convergence along the toe of the forearc, along the plate interface beneath the forearc and within that volume of crust affected by convergence. Time and space variations in the flow patterns of material through subduction complexes shape the internal architecture of continents.

The final high priority, which is complementary to and an extension of the state of stress program, is to establish the kinematics and dynamics of ridge axes and intervening transform faults. The mid-oceanic ridge system is the most continuous structural interface on the Earth's surface and is characterized by very high rates (a few centimeters to 16 cm/yr) of relative motion. This tectonic domain may represent the highest strain-rate environment on the Earth's surface and yet little is known about how stress varies along and across strike, the behaviour of faults at depth and the strain history of the upper mantle.

MAJOR SCIENTIFIC OBJECTIVES

Physical State and Dynamic Processes

Long-standing questions of lithospheric dynamics and evolution involve such fundamental problems as understanding the relative importance of plate-driving forces, physical, thermal and mechanical constraints on lithospheric structure and deformation, and the coupling between lithospheric and asthenospheric processes. We recommend that two globally-oriented initiatives be undertaken to address these problems: *Determination of the State of Stress and Physical Properties of Oceanic Lithosphere*, and *Establishment of Ocean-Bottom Geophysical Observatories*. In the case of both of these initiatives, major advances have taken place since COSOD I that indicate the potential for these intiatives to make unparalleled progress on some of the most fundamental problems in plate tectonics.

Determination of the State of Stress and Physical Properties of Oceanic Lithosphere

The list of problems that need to be addressed in this area are far-ranging and fundamental. In addition to the need to improve our understanding of the distribution and relative magnitude of the forces that drive (and inhibit) plate motion, other important problems include understanding the dynamics of transform faulting and ridge/transform interactions, the mechanical, thermal and rheological constraints on spreading, the state of stress, pore pressure and deformational properties in convergent margins, the relationship between upper mantle and crustal seismic anisotropy and *in situ* stress, the mechanical, thermal and rheological contraints on lithospheric flexure, and so on.

A number of scientific and technological developments over the past few years lay the groundwork for a major ODP initiative of measuring physical properties and *in situ* stress in ODP boreholes in the 1990's.

First, major advances have been made in both the tools and analysis methods available for determining physical properties. These include greatly improved geophysical logging methods for determining P- and S-wave sonic velocity, density, porosity, and resistivity, and utilization of such special geophysical tools as 3-component geophones (for vertical seismic profiling) and borehole magnetometers and gravimeters. It is more possible than ever to use borehole measurements to calibrate regional geophysical data and characterize crustal properties. Such new tools as the wireline packer-system may provide a rapidly deployable and efficient system in the 1990's for measurement of pore pressure and permeability.

The second major advance in this area in the past few years is the development and verification of an efficient, reliable and practical method for making *in situ* stress measurements in ODP boreholes. In many cases, it is possible to make literally hundreds of measurements of the orientation of the horizontal principal stresses in a single borehole by detailed study of stress-induced wellbore breakouts (Fig. 1) with acoustical imaging logging tools (Zoback and others, 1985). Dozens of case-studies on land have demonstrated the validity of this stress measurement method (Bell and Gough, 1979; Gough and Bell, 1981; Zoback and Zoback, 1987) and it has been successfully employed in two DSDP/ODP drill holes (Newmark and others, 1984).

Third, working on a number of continents around the world over the past few years, various investigators have now

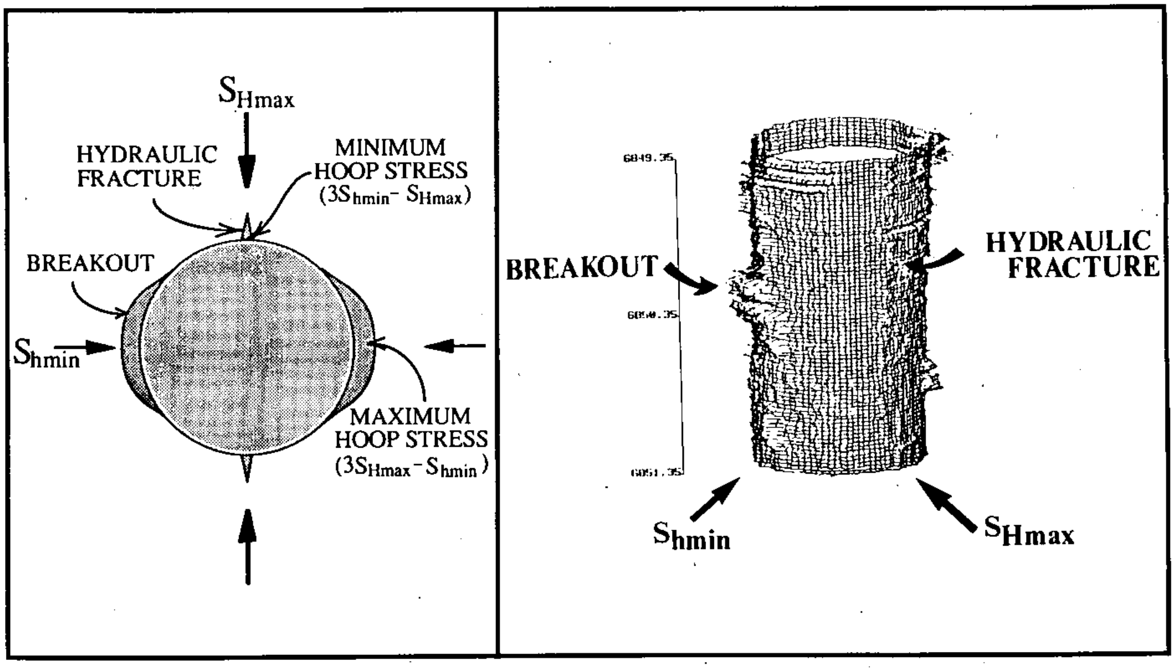


Figure 1. (Left) Theoretical representation of the relationship between stress-induced wellbore breakouts and hydraulic fractures and the *in situ* field. (Right) Three-dimensional image of a wellbore reconstructed from acoustic borehole televiewer data showing wellbore breakouts and a hydraulic fracture at right angles to each other.

compiled almost 2000 indicators of tectonic stress orientation and have found that the tectonic stress field can be successfully mapped and regionalized, providing dramatic improvements in understanding a number of continental tectonic processes (Zoback, 1987). Under the auspices of the Inter-Union Commission on the Lithosphere, these data are now being

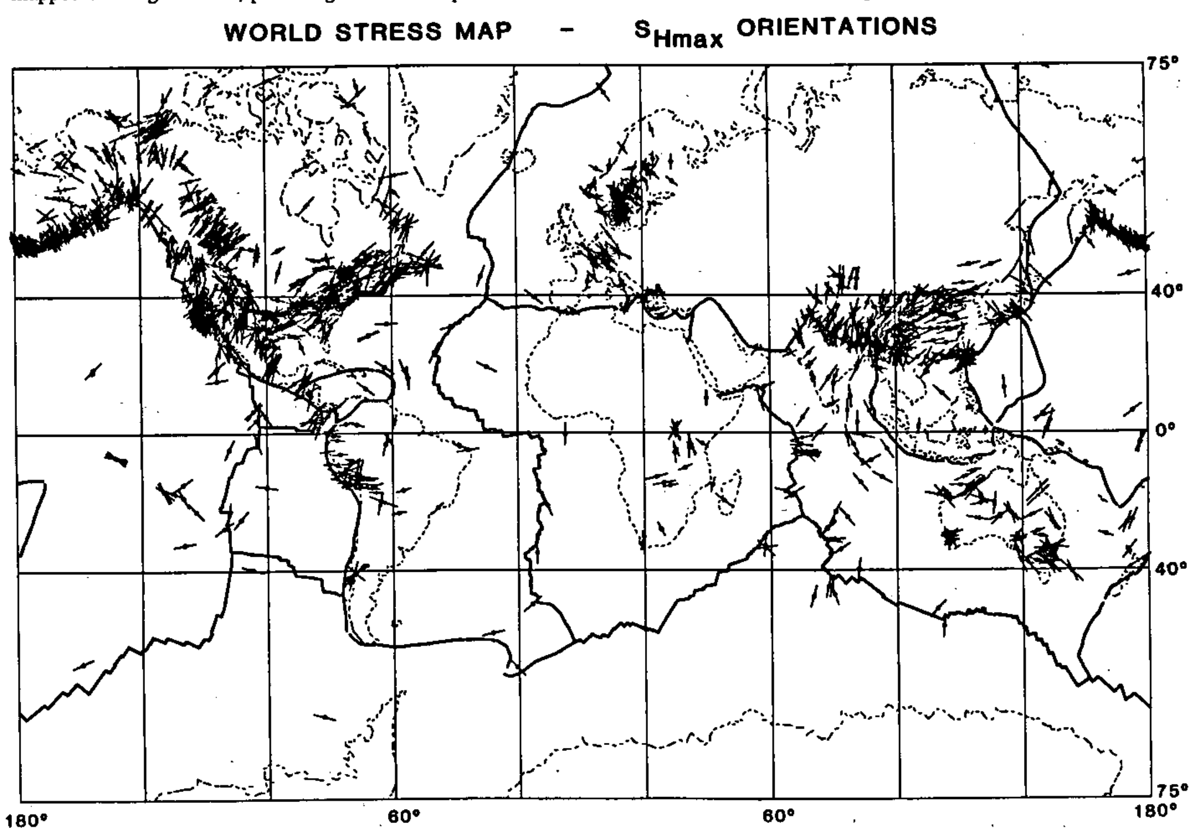


Figure 2. Preliminary compilation of *in situ* tectonic stress data around the world (Zoback, 1987). Data come from breakouts, earthquake focal plane mechanisms, *in situ* stress measurements at depth and post-Pliocene geologic indicators of stress.

compiled into a World Stress Map (Fig. 2) providing a global context in which data from the oceans of the world are badly needed to understand global processes.

Fourth, as a consequence of scientific developments often involving satellite technology, fascinating new data are available which require estimations of the stess at the scale of the plates to be understood. Thus, new geodetic techniques such as Satelllite Laser Ranging (SLR) and Very Long Baseline Interferometry (VLBI) are now measuring intercontinental distances to centimeter accuracies. Distances between sites on different plates are measured to find the present-day plate velocities (to be compared to the million-year-averaged velocities determined from seafloor magnetics) and distances between sites on the same plate are measured to test for plate distortion. Figure 3 shows the rates of change found with roughly four years of Satellite Laser Ranging data in the Pacific area and the Minster/Jordan predicted rates for these same baselines. If the Pacific plate does not deform, the distance between Hawaii and Huahine (Society Is.) should remain constant. There are only four years of data and yet undiscovered systematic errors may be biasing the result, but the present data (Fig. 4) suggest that the distance between Hawaii and Huahine is increasing. Similar VLBI data suggest that the distance between Hawaii and Kwajalein is increasing at about the same rate. If the oceanic plates are distorting at this rate in response to the forces pulling and pushing them, stress measurements within the plates should prove necessary to help us understand the processes involved.

Finally, over the past decade, there has been continued evolution and improvement of dynamic models of lithospheric driving forces, deformation and structure. Thus, an extensive "theoretical context" exists that requires data on state-of-stress and physical and rheological properties for verification (see, for example, Cloetingh and Wortel, 1985 ; Bergman, 1985 ; Wiens and others, 1985).

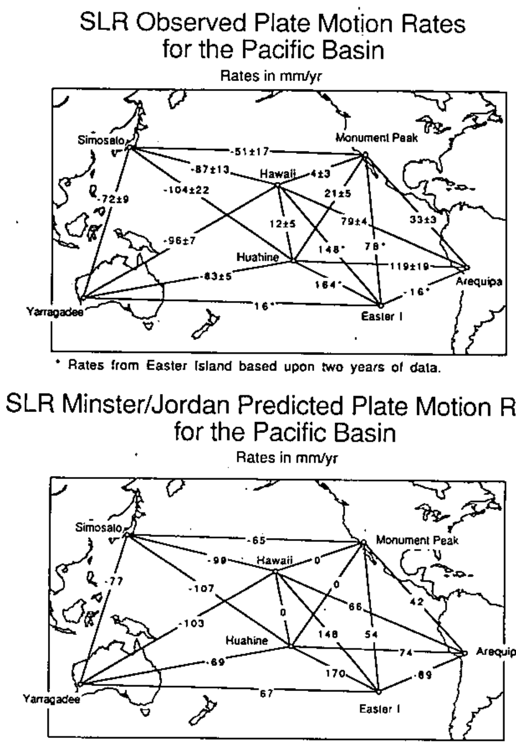


Figure 3. Observed rates of change of baselines in the Pacific determined with approximately four years of Satellite Laser Ranging data and the rates of change predicted by model RM2 of Minster and Jordan (1978). From NASA Crustal Dynamics Meeting (1987).

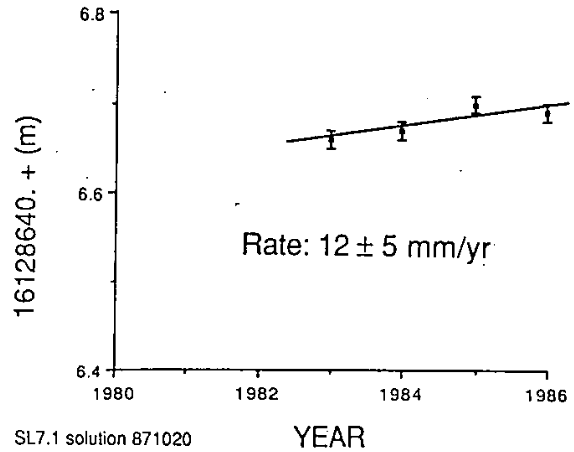


Figure 4. Satellite Laser Ranging measurements of the distance between sites in Hawaii and Huahine. From NASA Crustal Dynamics Meeting (1987).

Ocean Bottom Geophysical Observatories

The desirability of establishing ocean bottom and sub-bottom geophysical observatories in conjunction with drill holes has been obvious from the start of the Deep Sea Drilling Project. But no such observatories have been established for two principal reasons. One, that rocks cored from the drill holes have, by far, been the most important reason for drilling the holes. Two, it has not been clear that the requisite technology has been available for various aspects of such observatories - development of bottom and sub-bottom instruments, their emplacement, their maintenance and data retrieval. The reason for tying the ocean bottom/sub-bottom observatories to the drilling program is threefold. One, that it

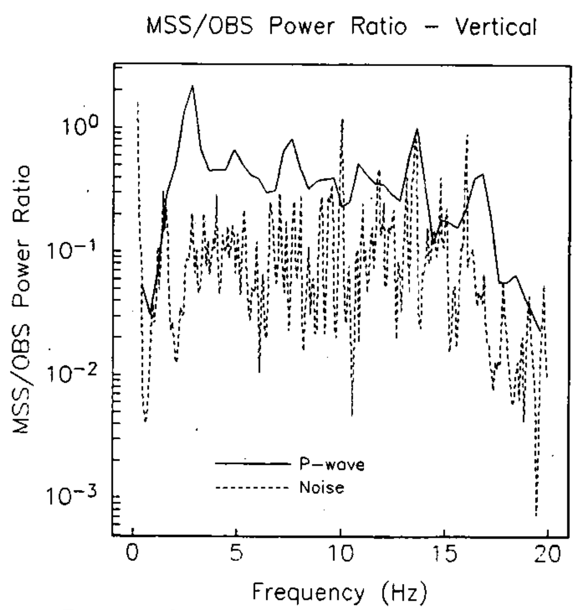


Figure 5. Comparison of ocean bottom (OBS) versus borehole (MSS) seismic data from the 1983 Ngendei Seismic experiment in the Southwest Pacific : MSS/OBS spectral ratio for P waves (solid lines) and noise (dashed lines). The borehole instrument enjoys a signal to noise advantage of about 7 dB below 10 Hz, and a 3-5 dB advantage between 10 and 20 Hz (from Shearer and Orcutt, 1987).

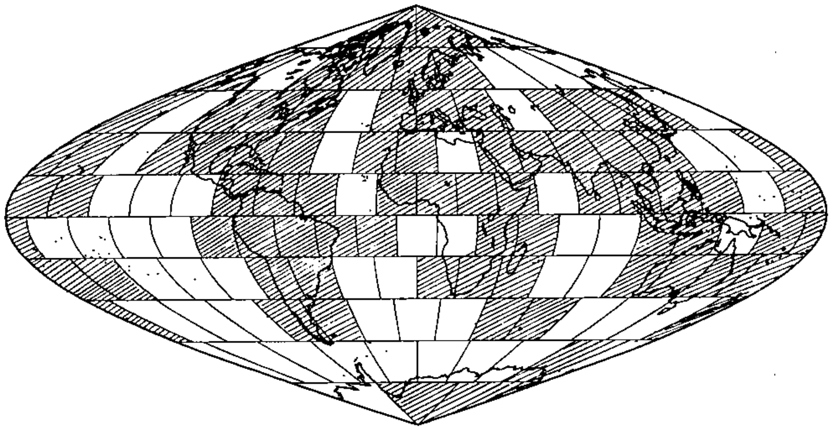


Figure 6. Expected global coverage with stations of the International Federation by 1992. Shaded cells contain or will contain at least one station. Note the relatively poor coverage of the oceans.

is very important to have information about the subsurface at the site of these observatories ; two, that emplacing instruments in the borehole reduces noise levels significantly for some instruments (Fig. 5) ; and three, that some experiments specifically require the emplacement of instruments at different levels in the boreholes.

It is critical for ocean-bottom seismic observatories to supplement and become an essential part of the global observing system (Fig. 6) over the next decade. Both short-period and long-period seismic observations are extremely important. Very broad-band seismograph systems emplaced in the drill holes are a necessary complement to the land-based Global Seismographic Network. The primary purpose of this type of observatory would be to monitor seismic activity on the ocean floor, and to record information needed in studies of Earth structure and earthquake source mechanisms.

The direct scientific benefits of the deployment of broad-band seismographic stations on the ocean bottom are :

(1) More uniform monitoring of the pattern of the stress release ; particularly the study of intraplate events in the oceans and major trench events.
(2) Higher, more uniform resolution of the Earth structure. Surface wave tomographic methods yield results that are subject to rather strong assumptions. Body wave tomography in the top 1000 km of the mantle is not possible in significant portions of the oceans, because of the lack of seismicity and the absence of seismographic stations. Lower mantle tomography also suffers from these drawbacks (Fig. 7).

Significant progress has occurred since COSOD I. The developments in seismometry presently allow us to extract from a single data stream all useful information in the teleseismic frequency band (Wielandt and Steim, 1986). Progress in electronics (24 bit A/D converters) allows us to preserve the needed linearity and dynamic range. The advances made using data from the sparse digital networks operating since the mid-1970's are spectacular. There are now tomographic maps of the

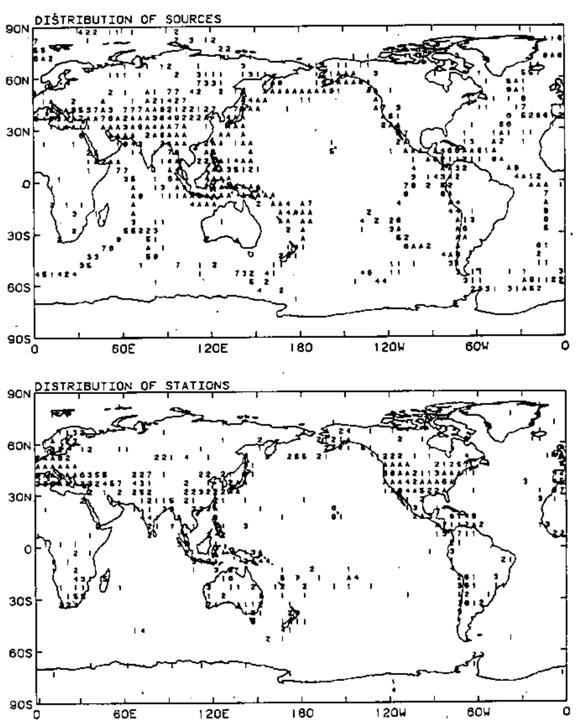


Figure 7. Distribution of sources and receivers available for a recent study of the structure of the lower mantle using P wave travel times for teleseismic distances (from Dziewonski, 1984).

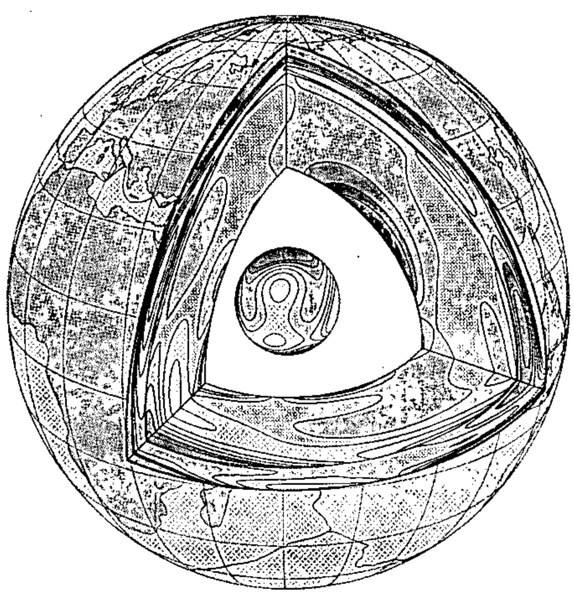


Figure 8. "Window through the Earth". A perspective view from a distance to the Earth's center of 35 000 km, showing regions of fast (dark) and slow (light) seismic velocities in the mantle and the inner core. Upper mantle models are obtained from the study of very long period surface waves, lower mantle models from travel times of body waves, inner core ones from splitting of free oscillations. A drawing by J.H. Woodhouse.

Earth's interior, reaching from the top of the lithosphere to the inner core of the Earth (Fig. 8 ; Dziewonski and Woodhouse, 1987). First maps of the topography of the core-mantle boundary were published this year (Creager and Jordan, 1986 ; Morelli and Dziewonski, 1987). The structure of the Pacific is anomalous at all depths, from the upper mantle to the core-mantle boundary.

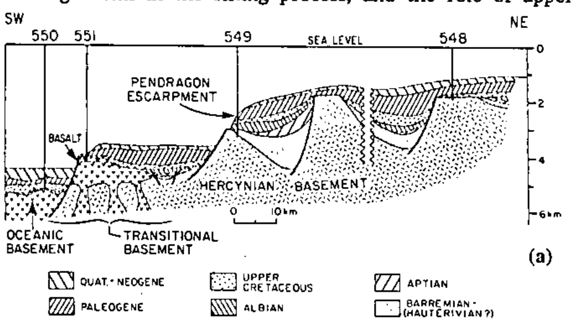
The digital data allow systematic analysis of the world's seismicity on an unprecedented scale. Tools exist now to analyze earthquakes in nearly real time and provide timely and more accurate tsunami warnings. Analysis of seismic waves caused by volcanic eruptions allows us to quantify an eruption very rapidly (Kanamori and others, 1984).

Significant progress has been made in the last four years in assuring improvement of the land-based coverage. Initiatives to modernize existing seismographic networks have been taken in several countries. In 1986 a new organization was formed : the Federation of Broad-Band Digital Seismographic Networks (Romanowicz and Dziewonski, 1986, 1987). The initial member networks of the Federation represent seven countries : Australia, Canada, China, France, Germany, Japan and the United States.

Rift Environments and Passive Continental Margins

Scientific Objectives

Passive (Atlantic-type) continental margins are primary storehouses of information concerning the crustal deformation processes which break up continents and initiate a crustal evolution that finally generates oceanic crust. During their earliest stages, passive margins must have resembled continental rift systems (*e.g.* East African or Rio Grande Rift) whereas their final active stages resembled oceanic rift systems. Recent advances in our understanding of rifting processes in continents, continental margins, and oceans lead to a strategy different from that outlined in COSOD I for studying passive margins. Collaborative efforts among researchers of these three regimes of rifting have developed new models for lithospheric evolution that include variations in the brittle/ductile deformation of the lithosphere, the variable role of magmatism in the rifting process, and the role of upper



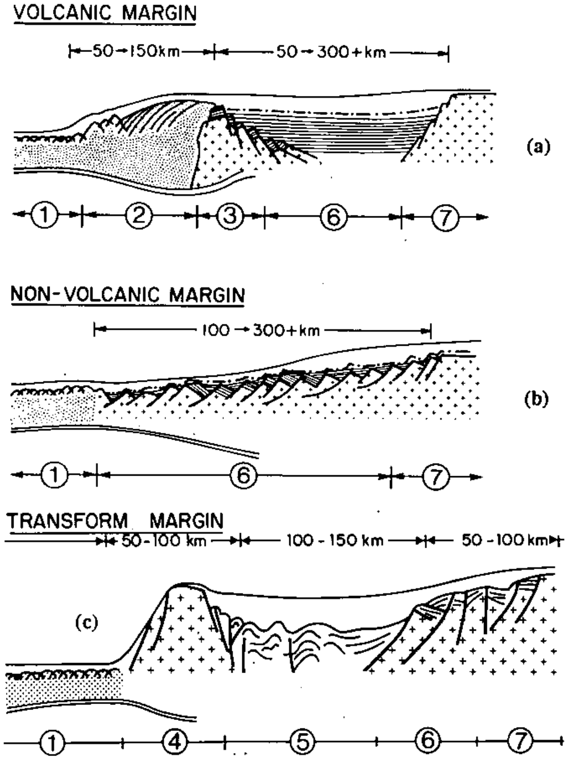
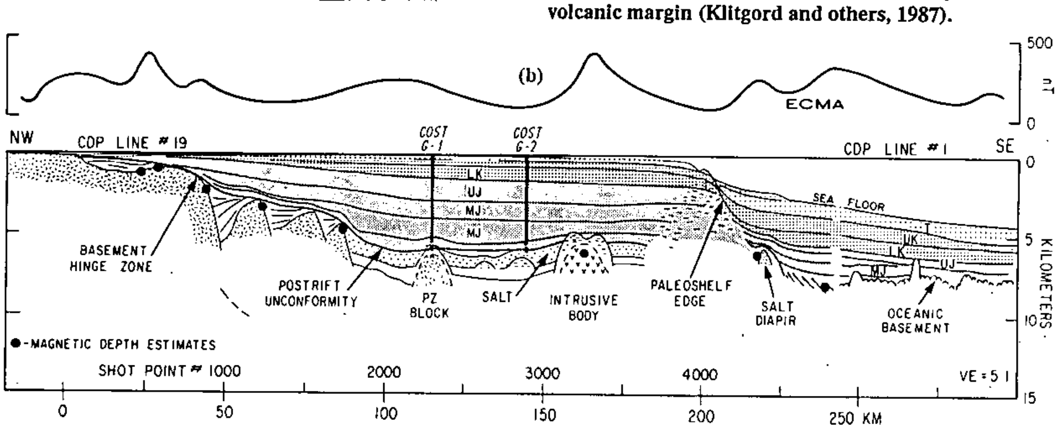


Figure 9. Comparison of the typical structural elements of (a) "volcanic", (b) "non-volcanic", and (c) rift-transform margins. The numbers refer to structures as follows : 1) the normal thickness oceanic crust, 2) the thick volcanic succession associated with the continent-ocean boundary of volcanic margins of which the seaward-dipping units form the upper sequence, 3) a structural high in continental crust that often occurs adjacent to the thick volcanic succession, 4) marginal fracture zone, 5) pull-apart basin on thinned crust, 6) thinned, subsided continental crust, 7) unstretched continental crust. The dot-dash symbol marks the stratigraphic level of breakup. Parallel ruled regions indicate sediments. From Mutter and others (1987) and modified from Sibuet and Mascle (1978).

Figure 10.

(a) Cross-section of the Goban Spur-Irish Sea margin in the vicinity of the DSDP Leg 80 drill sites. An example of a sediment-starved, non-volcanic margin (Graciansky, Poag and others, 1985).

(b) Cross-section of Georges Bank Basin on the U.S. Atlantic margin. An example of a heavily sedimented non-volcanic margin (Klitgord and others, 1987).



mantle convection and partial melting on crustal modification. Variations in the response of the lithosphere to the rifting process provide an opportunity to examine the relative influences of brittle and ductile deformation, magmatism, and metamorphism on lithospheric evolution. The physical character (structure, physical properties, geophysical signatures, etc.) of passive margins varies along individual margins, between flanking margins of the same ocean basin and between margins of different ocean basins : yet coherent patterns do persist. Most margins are segmented on a length scale of 400-1000 km with distinctive but relatively uniform structural characters within each segment. The segmentation spacing is similar on conjugate margins yet the structural character is often different for conjugate segments.

A least three different classes of passive margins have now been clearly identified (Fig. 9) : volcanic, non-volcanic, and rift-transform. Lithospheric deformation on non-volcanic margins (Fig. 9b) is dominated by block-faulting, brittle failure in the upper crust and ductile deformation in the lower crust and upper mantle over a broad zone (100-300 km). Magmatic activity is probably confined more to the deep parts of the lithosphere, with only minor volcanic activity in the upper crust. The Red Sea (active rift margin), Galicia Bank, northern Biscay, and Goban Spur-Irish Sea (Fig. 10a) margins are sediment-starved, non-volcanic passive margins, whereas the Georges Bank margin of the eastern United States represents a heavily sedimented example of a non-volcanic margin (Fig. 10b). Multiple-layer pure-shear models (Fig. 11a) and simple-shear along low-angle detachment-surface models (Fig. 11b) have been developed to explain this type of margin structure.

In contrast, volcanic passive margins (Fig. 9a) (Roberts and others, 1985) are narrower and contain thick igneous crust between continental and normal oceanic crust. The Outer Vöring Plateau (Fig. 12), western Rockall Bank, and the east Greenland margin are in this category. A thick zone (as much as 3-5 km) of seaward-dipping volcanic units overlies a lower crust which is 15-20 km thick and is characterized by seismic velocities between 7.2 and 7.5 km/sec. Margins of this type appear to develop along the flank of an earlier rift basin, creating a marginal plateau. Pure-shear models, with adiabatic upwelling, elevated thermal anomalies, and convective partial melting (Fig. 13) have been developed to explain this type of margin structure (Mutter and Buck, 1986 ; Hinz and others, 1987). It has not been established, however, that the convective component of these models is essential (White, 1987).

Rift-transform margins (Fig. 9c) evolved within a thermomechanical regime that included a significant component of strike-slip shear as well as extensional strain deformation. Some of the best examples are along the early plate boundary connections between the South Atlantic and both the central Atlantic (southern-West African and northeastern South American margins) and Indian Oceans (Falkland Plateau and Agulhas/South African margins). This type of margin evolves from continental-continental shearing (*e.g.*, a San Andreas fault type system) to oceanic transform zones (*e.g.*, the Gulf of California). Models for the thermomechanical evolution of this type of margin (Fig. 14) are just now being developed.

Primary objective of an ocean drilling program must be to improve our understanding of these deformation, magmatic, and modification processes of rifting and the causes of variations in the resultant lithotectonic regimes. What is the role and nature of underplating and surface magmatism in crustal modification ? What are the roles of high-angle normal

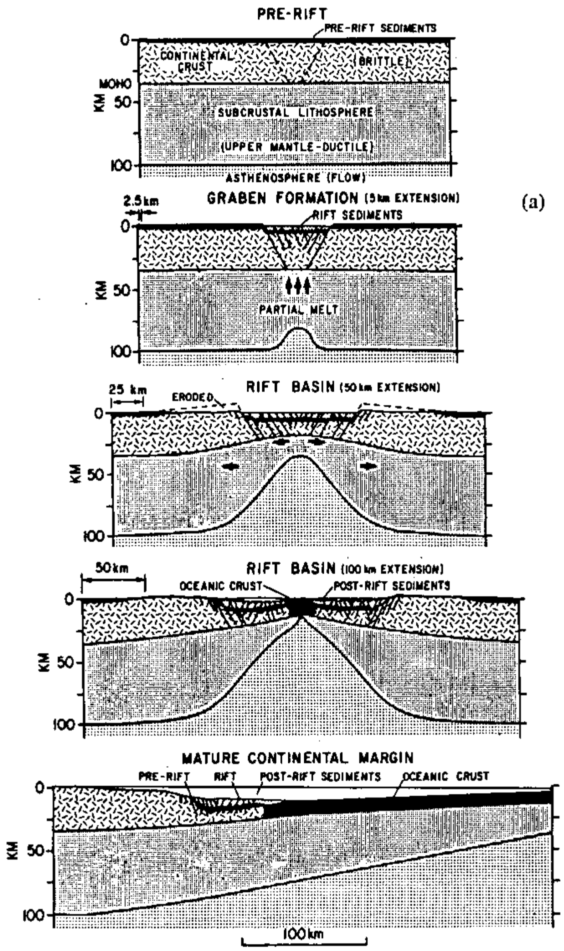
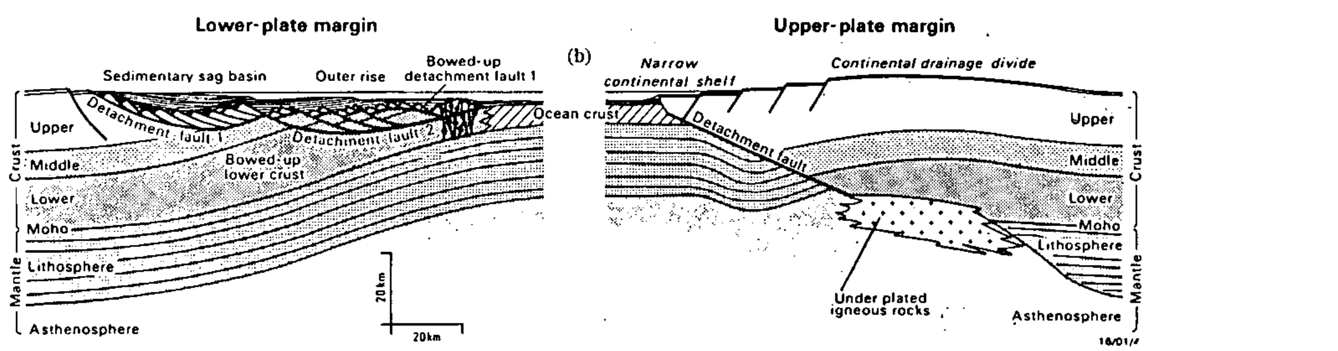


Figure 11. Schematic diagram illustrating crustal evolution model for Atlantic-type margins based :

(a) on pure-shear deformation (from Sclater and Hellinger, 1983) ;

(b) on simple-shear along low-angle detachment faults (Wernicke, 1985 ; Lister and others, 1986).



faulting, listric faulting, and low-angle detachment faulting on the brittle-ductile deformation of continental lithosphere? How do pre-existing lithospheric structures influence margin evolution during rifting? Are low-angle detachment faults an important element for the development of rifted margins, and are deep crustal levels elevated to drillable depths as a result of denudation associated with extension along these detachment faults or of uplifting associated with mantle diapirism like in Zabargad Island in the Red Sea (Nicolas and others, 1987)? What is the metamorphic history of the lithosphere layers? As was demonstrated on ODP Leg 103 on the Galicia Bank margin, ductile deformation, metamorphism and partial melting experienced by basement rocks can be observed and studied on oriented cores. How do long-term shearing and migrating thermal sources influence crustal modification on rift-transform margins? In order to answer some of these questions, we must obtain samples of crustal rocks in the vicinity of the major fault surfaces that bound fragments of rifted crust and merge into the brittle-ductile boundary in the crust.

There still exists considerable uncertainty about the nature of major geophysical "edge" anomalies (such as the East Coast Magnetic Anomaly) near the boundaries between continental and rift-stage crust and between rift-stage and oceanic crust. Some of these "edge" anomalies do have a segmented character similar to that found in oceanic crust (Schouten and others, 1985) and are located within the transition zone that separates continental and oceanic crust. We need to understand the crustal variations that cause these "edge" anomalies and their segmentation and to establish when the "edge" anomalies and segmentation develop during the crustal evolution process. Are they associated with the fragmentation of continental crust or with the initial magmatism phase of the seafloor spreading process?

The formation of sedimentary basins along continental edges is a related and fundamental aspect of passive margin evolution that we are also striving to understand. Besides containing the most continuous geologic record of the rifting process, the sedimentary units within these basins are economically important for the hydrocarbon resources which they contain. Although the record of vertical movements on passive margins was emphasized in the COSOD I Report, it has since become clear that the record of horizontal movements of synrift/prerift crust and upper mantle (*e.g.*, rotation or translation along low-angle faults and mantle diapirism) is equally important. Our ability to interpret the sedimentation record of the rifting process is limited not only by our understanding of the paleoenvironmental influences on this record (*e.g.*, sea-level fluctuations, basin-wide ocean current patterns, paleoclimate and paleogeography, on postrift sedimentation), but also by our knowledge of the underlying crust and upper mantle (composition, structure, thermal state, flexural rigidity, state of stress, etc.) as a function of space and time. Thus it is essential that we obtain more direct information concerning the nature of deep crust and overlying sediments using a combination of geophysical (*i.e.*, remote-sensing) and direct (*i.e.*, sampling) observations.

Scientific Approach and Role of Drilling

Rifting on passive margins represents an intermediate phase between continental and oceanic rifting. Therefore, margin studies must be integrated with these other rift studies, to incorporate both observation constraints and model predictions. The investigation of passive margins must be aimed at acquisition of information concerning the timing, nature and magnitude of crustal deformation during the synrift and early postrift phases of margin evolution, as well as more complete records of the postrift phase.

The overall objective of passive margin studies is to recognize and characterize the lithosphere structure transitional between oceanic and continental lithosphere and to understand the geologic processes that control the evolution of this lithosphere. In the COSOD I Report, this research initiative was subdivided into four components: 1) the detailed history of vertical movements (i.e., uplift and subsidence) that occur at passive margins during their evolution, 2) the deep crustal structure of passive margins, 3) the thermal and mechanical evolution of passive margins, and 4) "global" unconformities that developed in response to the synchroneity of tectonic and sea-level events at passive margins. We have made substantial progress towards all of these objectives, resulting in a need to refocus each based on past results.

Most of the detailed history of vertical crustal movements comes from the sedimentary record, with additional constraints provided by synrift volcanic activity. This record includes the prerift, synrift and postrift geologic history. However, our detailed knowledge is biased towards the synrift record on sediment-starved margins. As a result, our knowledge of the prerift, synrift, and early postrift sediment distribution is often inadequate for determining the timing, magnitude and nature of crustal deformation during the most active period of lithosphere evolution - the rifting phase. Studies of the mildly deformed passive margin of the Ligurian Tethys in the Western Alps indicate multiple rifting phases (Lemoine and others, 1987), for which there is some evidence on other passive margins. What is the role of multiple rifting events on margin evolution? Some rift zones appear to be constructed by a series of successive rifts, with variable periods of quiescence, while others are shifted in space as well as time. It is essential that we obtain a detailed record of both late prerift/early synrift and late synrift/early postrift sediment sequences in order to establish the timing, change in paleoenvironment, and change in lithospheric deformation as the rifting process starts and eventually gives way to seafloor spreading. Deformation of the late prerift sedimentation record (faulting, erosion, non-erosion, uplift, etc.) coupled with the early synrift deposition/erosion record provides key information about the early synrift phase. On volcanic margins, as documented recently by ODP Leg 104, most of the synrift record is incorporated into seaward-dipping volcanic units. What is the variation in petrologic and geochemical signatures of these units along and across the margin? For example, is there a distinctive change in magma source along and across the margin which can be related to deep crustal/upper mantle evolution? Does the synrift sedimentary component of these volcanic piles vary, indicating changes in paleoenvironment and reflecting changes in magmatic sources? We must also strive to identify the role of brittle deformation on those margins.

Our knowledge of the deep crustal structure of margins must include samples of the prerift "country rock" and synrift strata (igneous and sedimentary). Petrologic, geochemical, and rheologic data of these rocks are essential for calibrating geophysical studies, the primary source of regional information concerning crustal structure and composition. Variations in deep crustal rock properties in space and time are important elements influencing a margin's response to extensional and thermal stresses (brittle-ductile deformation, magmatic activity, conductive-convective flow) and to sediment loading (flexural rigidity).

Thermo-mechanical models for passive margin evolution are becoming more diverse as a result of influences from studies of both continental rifts and mid-ocean ridge spreading systems. Both spatial and temporal variations in crustal properties, including composition, thickness, flexural rigidity, thermal state, state-of-stress, etc., are expected as a result of the brittle/ductile failure of continental crust, convection in the upper mantle, and the crustal modification from partial melting, adiabatic upwelling and underplating of new crustal material. It appears clear that some passive margins (non-volcanic) more closely resemble continental rifts, whereas others (volcanic) are closer to oceanic rifts. Intermediate types of passive margins

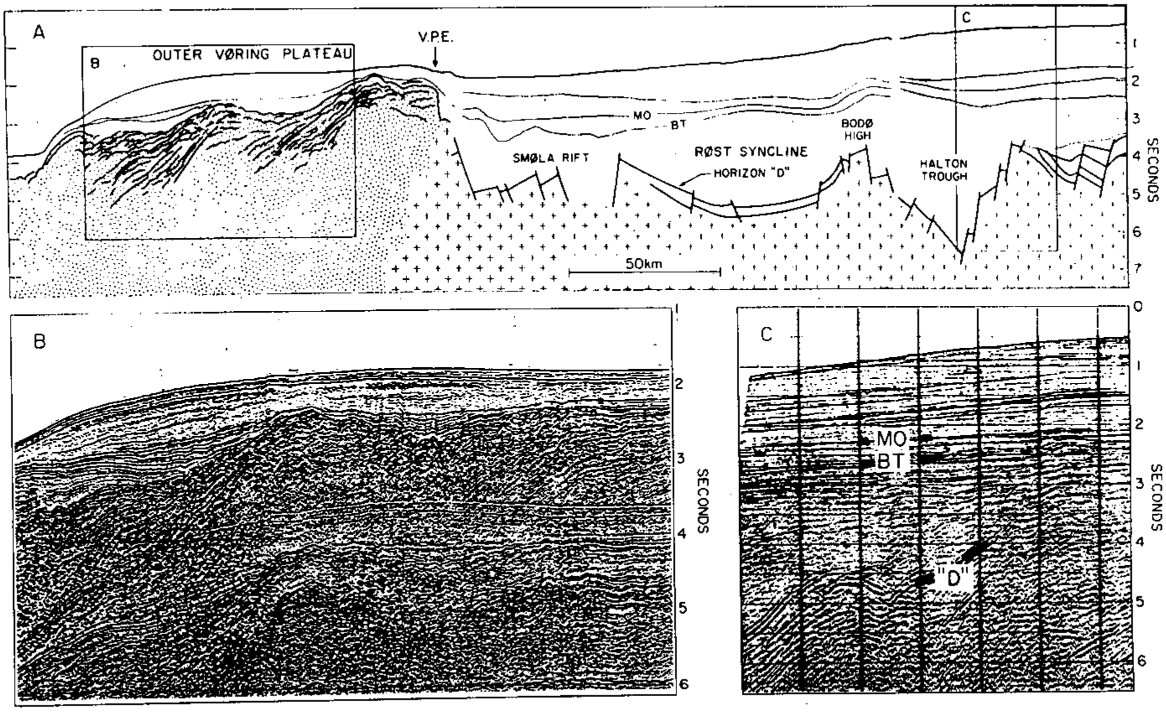


Figure 12. Cross-section of the Norwegian margin and Outer Vöring Plateau. An example of a volcanic type margin (Mutter and others, 1987).

probably also exist where thermo-mechanical models and observations can be studied to see if there is a true continuum in crustal rifting processes. For example, are all volcanic-type margins preceded by an aborted non-volcanic rift phase (as in the North Atlantic), and are non-volcanic rift margins followed by a brief "volcanic" rift phase before converting to seafloor spreading (as is true, for example, on the Goban Spur margin) ?

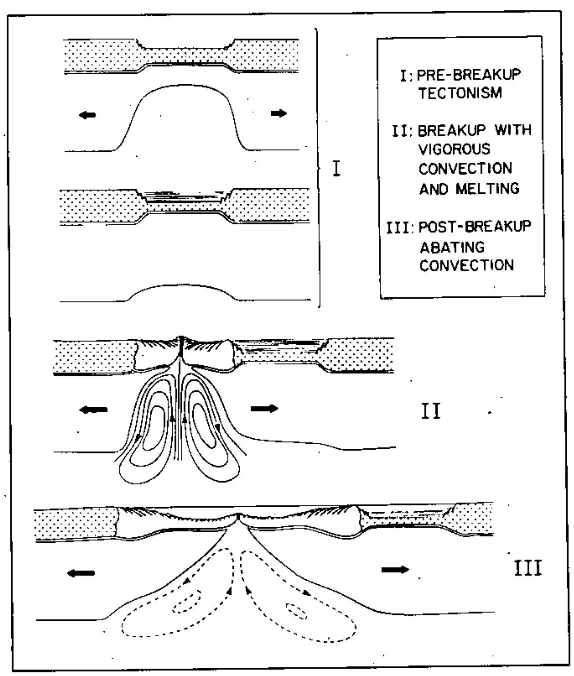


Figure 13. Schematic diagram illustrating the main stages in the evolution of a volcanic passive margin (Hinz and others, 1987 ; Mutter and others, 1987).

Evaluation of these models is dependent upon more detailed information concerning the deeper crustal evolution in space

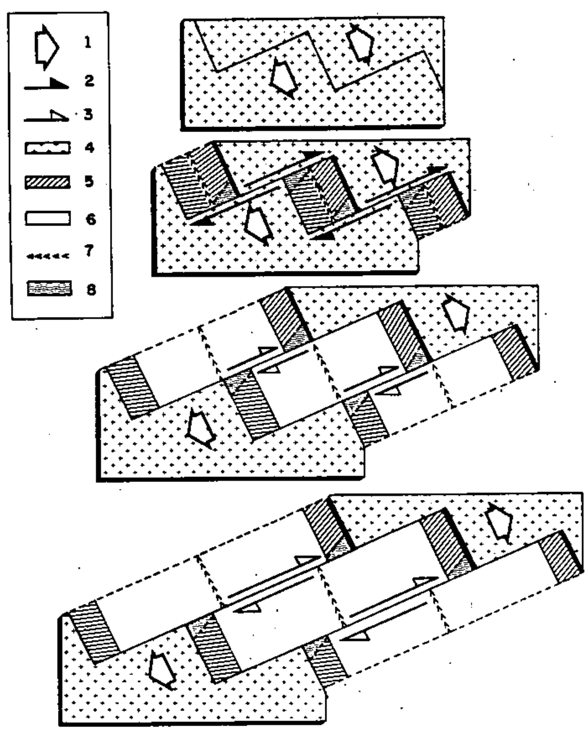


Figure 14. Schematic diagram illustrating the main stages in the evolution of a rift-transform margin: 1) divergence, 2) and 3) transform motion between respectively continental and oceanic crust, 4) normal continental crust, 5) thinned continental crust, 6) oceanic crust, 7) ridge axis, 8) marginal ridge (Mascle and Blarez, 1987).

and time. In addition, better thermo-mechanical models are needed for rift-transform margins which at present also suffer from a lack of observational information.

Postrift evolution of passive margins is dominated by the accumulation of sedimentary rock under the influence of competing tectonic processes (thermal cooling and sediment-loading subsidence), paleoceanographic processes (sea-level fluctuations and ocean basin circulation patterns), paleoclimatic fluctuations and variations in sediment sources. The evaluation of "global" unconformities and their relationship to tectonic and sea-level events is still an essential objective of scientific ocean drilling, enabling us to identify and calibrate the relative contribution of each process to margin evolution. A more clearly defined tectonic component is required in order to estimate the changes in deep crustal structure (in space and time) associated with the cessation of rifting. For example, how much of the present observable structure is a result of lithospheric "aging" following rifting ? This postrift record can only be achieved by the drilling of substantial sedimentary thickness (at least 3-4 km) in order to acquire adequate biostratigraphic and paleo-environmental resolution at "standard-reference" sites along the margins of individual ocean basins. These sites must be in regions that are remote from major paleoceanographic gateways and in regions adjacent to these gateways.

Mid-Oceanic Ridge System

The complex, interlinked processes of magmatism, deformation and lithospheric evolution that characterize the mid-oceanic ridge system are only defined in the broadest terms. A major aspect of our understanding of the generation and evolution of oceanic lithosphere is to elucidate the dynamics of these processes by carrying out a range of investigations and *in situ* observations at key diagnostic locations along and across the ridge system.

Scientific Problems

The mid-oceanic ridge system, composed of ridge segments and linking ridge-axis discontinuities (transform faults and discordant zones) of variable length, is a world-encircling tectonic lineament that is 70 000 km long and, as such, is a fundamental tectonic element of the Earth. The Earth's mantle rises beneath the ridge segments as the lithospheric plates separate, leading to pressure-release melting. The episodic emplacement of these melts at shallow levels beneath the ridge axes at discrete locations segments the ridge into independent magma reservoirs, which cool and solidify to create oceanic crust. The ridge segments have an arch-shaped along-axis topographic profile ; a depth minimum is located approximately midway along the ridge segment and depths increase toward the ends of the segment which are marked by transform faults and ridge-axis discordant zones (overlapping spreading centers, zero offset transforms) (*e.g.* Schouten and Klitgord, 1982 ; Francheteau and Ballard, 1983 ; Macdonald and Fox, 1983). Strong along-axis gradients in other characteristics (*e.g.* basalt chemistry, crustal thickness, distribution of hydrothermal activity) have been documented as well (Langmuir *et al.*, 1986 ; Detrick and Purdy, 1980 ; Fox and Gallo, 1984 ; Thompson *et al.*, 1985). There is a growing consensus that the distinctive, arch-shaped along-axis profile of a ridge segment is the product of buoyant forces caused by the distribution of melt at shallow levels within the upper mantle, and that the central high within a ridge segment marks the place along the axis where partial melt is preferentially concentrated (Schouten *et al.*, 1985 ; Macdonald *et al.*, 1984 ; Crane, 1985). This concept is supported by careful structural mapping in ophiolite complexes where the shape, size and spacing of diapiric structures can be established (Nicolas and Violette, 1982). The magmatic processes along the ridge dominate the volcanic flux of the Earth, creating on the order of 20 cubic kilometers of new lithosphere every year. Spatial and temporal variations in these melt-generation processes (*i.e.*, depth, extent and degree of partial melting), coupled with the tectonism of the ridge axis, create variations in crustal morphology, structure, igneous stratigraphy and composition, and influences the segmentation geometry of the ridge crest.

The skin of oceanic lithosphere created along the ridge axis thickens continually away from the ridge and represents a mechanically strong boundary layer that overlies weaker, ductile mantle. Along the ridge segments and linking ridge-axis discontinuities (transform faults and discordant zones), the newly formed and thickening lithosphere is subjected to stresses. Earthquake focal mechanism studies and theoretical studies indicate that there are a number of important sources of stress in the oceanic lithosphere : differential contraction due to cooling (*e.g.* Turcotte, 1974 ; Bergman and Solomon, 1984), normal and shear stresses focused at the base of the lithosphere by mantle flow and melt segregation processes (*e.g.* Sleep, 1969 ; Lachenbruch, 1973), forces generated by ridge axis topography (*e.g.* Richardson and others, 1979 ; Fleitout and Francheteau, 1983), and forces transmitted to the ridge axis through the lithospheric stress guide (*e.g.* Wiens and Stein, 1983). The resolution of these forces coupled with the mechanical properties of the rocks comprising the lithosphere will control the patterns and styles of deformation (*i.e.*, fault orientation, relief and sense of motion ; petrofabric characteristics). Models for the thermal and mechanical evolution of oceanic lithosphere predict that the state of stress will change in a variety of ways along and across the axis of the ridge. For example, complex deviatoric stress patterns are predicted as the oceanic lithosphere cools and thickens following its formation at the axis (*e.g.* Parmentier and Haxby, 1986), as ridge-transform intersections are approached (*e.g.* Phipps Morgan and Parmentier, 1984), as a ridge tip propagates into old lithosphere (*e.g.* Phipps Morgan and Parmentier, 1985) and at the tips of overlapping spreading centers (Pollard and Aydin, 1984). We wish to test these models in key tectonic environments and to establish the state of stress along the axes of accretion and to define the strain history of the rocks that comprise the crust and upper mantle.

Scientific Approach and Role of Drilling

The wide variety of temporal and spatial scales over which the magmatic, tectonic and lithospheric evolution processes operate to create oceanic lithosphere necessitates that observations must proceed on a broad and coordinated front, ranging from a global investigation of the ridge system to site-specific investigations.

The global scale perspective, which would involve satellite observations and regional mapping, is needed in order to establish the range of crustal generation environments (*e.g.* fast or slow, symmetric or asymmetric, normal or oblique, high or low magmatism, ridge-transform intersections, propagating ridges, etc.). This perspective would then be enhanced by a series of nested regional and site-specific surveys located at specific locations along those ridge segments considered to represent a critical component of the crustal generation spectrum. The full range of geophysical and geological investigations (seismic reflection and refraction profiling, potential-field measurements, microearthquake investigations, basement sampling by dredge and submersible, structural mapping with high resolution imaging instruments) would be implemented in these areas of interest to define, in three dimensions, the morphological, structural and compositional architecture of the oceanic lithosphere. These data would provide essential information about how the architectural parameters of the oceanic lithosphere vary at regional scale with respect to age and plate boundary geometry.

This regional perspective will be limited, however, without the insights obtained by direct sampling and *in situ*

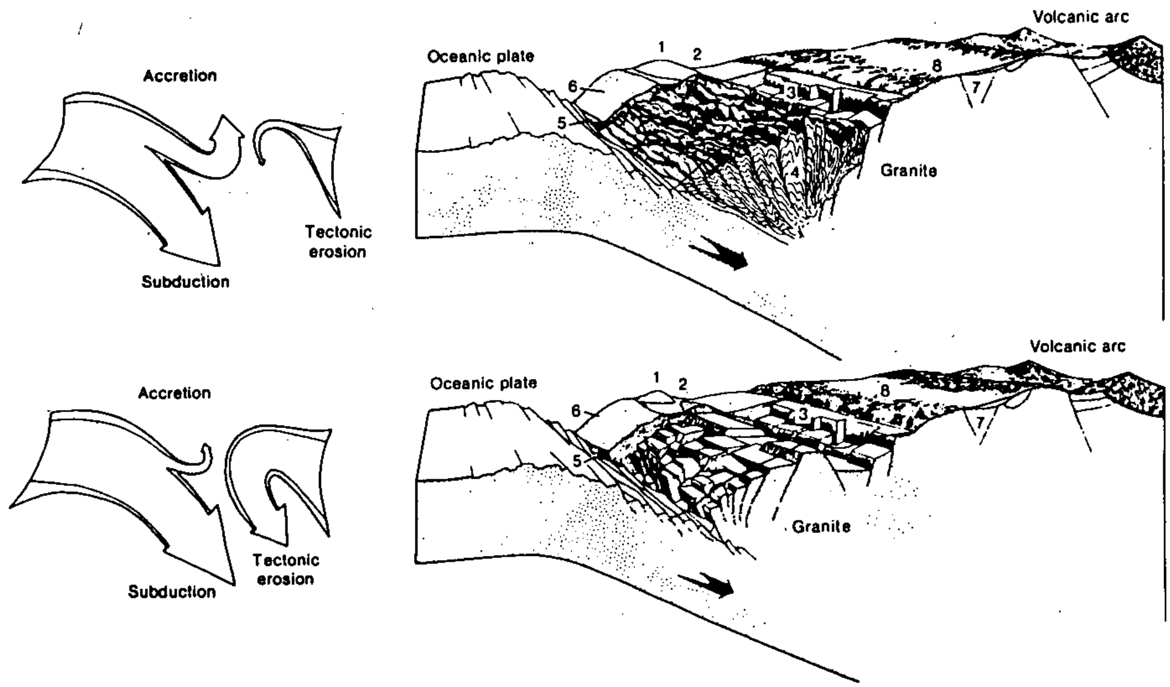


Figure 15. Accretionary and erosional end-members of convergent margins (Coulbourn, 1986).

measurements of the deeper lithosphere by drilling. The samples recovered will record the strain history and composition of the rocks. Laboratory measurements of the mechanical and electrical properties of the recovered rocks will make it possible to attach geologic characteristics to the physical properties of the oceanic lithosphere defined at a regional scale by geophysical observations (seismic velocity, seismic stratigraphy, electromagnetism, magnetism, gravimetry, heat flow). The drill hole is also a probe into the lithosphere, and *in situ* stress measurements with downhole logging are essential to define the state of stress and physical properties of the rocks at depth. Furthermore, some of these holes will be used as long-term observatories to define the dynamic processes affecting a given tectonic domain. Borehole monitoring would involve strain meters, as well as other geophysical tools.

Only a coordinated and multi-faceted geophysical and geological approach such as the one outlined above will resolve the processes that are responsible for the creation and development of oceanic lithosphere along the mid-oceanic ridge system.

Convergent Margins

Scientific Problems

Since COSOD I there have been significant advances in the understanding of convergent margins, in large part related to ocean drilling. The distribution of geologic properties and features has been better delineated, and variations among different convergent margins have been clarified. Unfortunately, there has been little progress in answering such basic questions as why these variations exist and how the causative processes operate. This slow progress reflects the very demanding environmental conditions at convergent margins, which in turn led to technical drilling problems that must still be overcome. Rather than update the objectives of COSOD I, we have chosen to focus on a few basic problems.

One basic and unifying problem is to understand the processes responsible for the spectrum of responses to plate convergence, not only at the toe of the forearc but along the plate interface beneath the forearc and also within that volume of crust affected by convergence. On a grand scale, this spectrum represents variations in the flow pattern of material through subduction systems. Such flow patterns control fundamental processes, such as the evolution of the continents and much of their internal architecture. These patterns also underlie aspects of geology of direct relevance to society, including mineral deposition and natural hazards like earthquakes and volcanoes.

Although studies of a convergent margin should be concerned with the entire system, we have focused at this evolutionary phase of the drilling program the drill-related studies into those near the toe of the forearc rather than those related to processes in the interior of the margin. This choice emphasizes the more direct and immediate solution of problems by drilling in the toe region rather than to the rear, where most of the process-oriented questions concern rocks far below the reach of the drill. This choice also underlies the higher priority that we assign to studies of the flow trajectories in the toe of the forearc where we already have a great deal of information.

The early, simple model in which crust was subducted beneath forearcs with offscraping of its sediment cover has been replaced with a more realistic spectrum of responses, from offscraping and accretion, through simple subduction with minimal transfer of material, to tectonic erosion and removal of forearc material (Fig. 15). There is also a wide range in the properties of the crust converging on the forearc, from basinal oceanic crust to topographically high, buoyant features such as seamounts, aseismic ridges, oceanic plateaus, continental margins and active spreading ridges. This dimension of variability is associated with the general topic of collision tectonics, but is clearly closely related to other aspects of convergence.

A primary problem in both aspects, spectrum of responses and dimension of variability, is to understand how and why the different conditions operate; not merely describing them, but probing their mechanical and chemical behavior. This approach could be viewed as the search for examples of forearcs where certain aspects are optimally

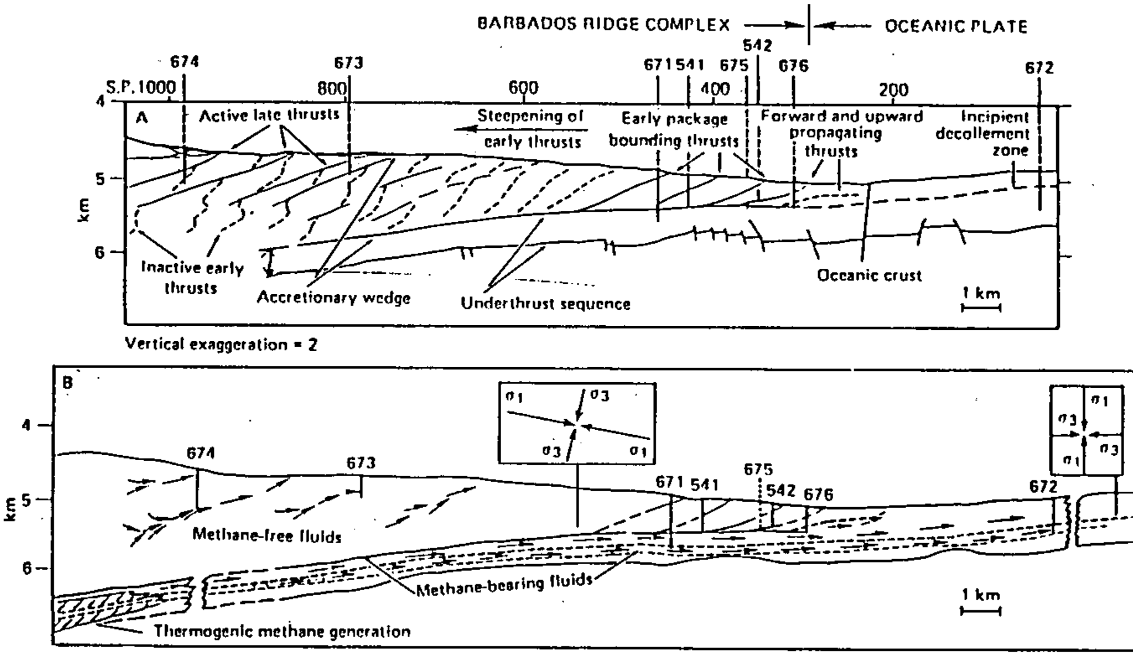


Figure 16. Details of the toe of an accretionary prism as outlined by ODP Leg 110 (Moore and others, 1987).

expressed and treating those forearcs as natural experiments from which to extract quantitative parameters. However, no matter how elegant an experiment is constructed, it must be correctly placed in a historical or evolutionary context, which will require a general knowledge of the geologic history of the arc-trench system.

Scientific Approach and Role of Drilling

In this section we will examine the roles played by the range of material transfer and of crustal types on the processes taking place in the forearcs of subduction zones.

Dealing with the spectrum of material transfer, we are concerned with the trajectories of materials in the zone where the downgoing plate first contacts the upper plate; material transfers between plates as well as along the plate boundary. Clearly, boundaries along which very thick sediments converge are more likely to be sites of frontal accretion, while those subducting crust with thin sediment covers and irregular basement topography will be more prone to non-accretion or erosion, but this correlation is far from perfect and does not explain the mechanics involved. Other factors, such as the mechanical properties of material at the top of the downgoing plate, the rate of convergence and the obliquity of convergence probably also have direct or indirect effects.

Frontal accretion is the best understood response (*e.g.* Karig, 1986; Moore and others, 1987), because the resultant structures are often clearly imaged on seismic profiles and because several drill holes have penetrated well into the toes of accretionary prisms (Fig. 16). Although there is much to clarify concerning the nature of offscraping, the questions to be addressed over the next decade are more advanced than for other types of responses.

Accretionary prisms constitute a natural experiment, in which porous sediments are deformed and consolidated under differential stress. These are very fundamental processes about which we have much to learn. On an intrinsic level, we need to quantify and relate: strain (finite strain, strain rate, deformation mechanism, fabric); stress (orientation, deviatoric stress, pore pressure); physical properties (porosity, permeability, temperature); and mechanical parameters (strength, cohesion, internal friction, compressibility). In the context of the accretionary prism we must determine: (1) how deformation is distributed throughout the prism; (2) how dewatering is distributed, *i.e.*, what are the mechanics and paths of water flow, what geochemical fluxes are involved, and how is water flow related to stress levels; and (3) what factors control the mechanical partitioning of the incoming sediment cover into that section offscraped by thrusting and folding and that section subducted beneath the prism toe ?

Non-accretion refers to the relatively common situation where there is neither accretion nor erosion at the toe of the forearc. This response can be viewed as a limiting case of either accretion or erosion, but how weak sediments can be subducted beneath a lithified forearc rather than being scraped off by it is a question that must still be answered.

Tectonic erosion may be another common response, but the responsible processes are still enigmatic. Recent studies suggest that removal of forearc material may be by massive slumping into the trench (Fig. 17), where a short-lived accretionary prism develops (*e.g.* Von Huene, 1986). Other studies infer erosion from large and rapid increases in water depth over forearcs (ODP Leg 112, 1987). How and why large-scale slumping is initiated and why the slumped material is subducted rather than accreted is yet to be answered. Changes in depth of the forearc surface must be more explicitly linked to processes that change the prism thickness, as opposed to processes that change the depth of the plate interface. In short, extensive study of the basic geometries, kinematics and histories of such margins must be undertaken before more specific questions can be addressed.

Rates and the relative direction of convergence are also factors that could affect the trajectories of incoming material. Convergence rates affect sediment fill in trenches, which is reflected in variations of structural style, possibly through different porosities and pore pressures. The angle of convergence relative to the trend of the plate boundary gives rise to a continuum in response from subduction to transpression to simple strike-slip motion. The general

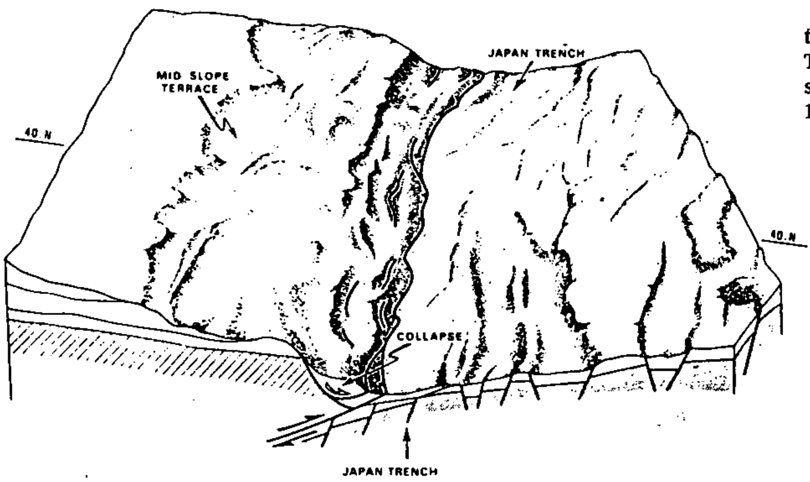


Figure 17. Synthetic model of tectonic erosion along the Japan Trench based on extensive seismic and submersible data (Cadet and others, 1987a).

response to this continuum is beginning to receive attention but almost nothing is known about the variations in forearc structural fabric as a function of obliquity.

A scientific program to explore the variations in trajectories of material within forearcs must use a system approach, with carefully integrated elements undertaken in the appropriate sequence. Drilling must be guided by extensive seismic profiling, with suitable parameters and adequate migration. Because the tiny column of core recovered by drilling must be extrapolated to a volume many orders of magnitude larger, and because forearcs are heterogeneous environments, drill holes must be sited on the basis of detailed bathymetric (*e.g.* SeaBeam) or sidescan sonar (*e.g.* SeaMARC) data, and near-bottom studies using submersibles and deep-towed instruments.

The second important parameter in the response of forearcs is the spectrum of crustal type of the downgoing plate. Crustal characteristics of importance include topography, crustal thickness and density, thickness and character of the sediment carapace, and the thermal conditions. Of particular interest are effects of subduction of non-typical oceanic crust - commonly termed "collision".

Topographically high features, such as seamounts, aseismic ridges (*e.g.* fracture zones, remnant arcs, etc.) and oceanic plateaus commonly are carried into convergent margins, with uncertain results. The idea that topographic highs are invariably accreted has clearly not been supported by recent detailed surveys, which show that even relatively large features can be subducted beneath the forearc with relatively little impact (Fig. 18). Indentation of the forearc is common, but this could represent either removal or deformation of material. Dredge hauls suggest that minor accretion can occur, but do not reveal the process by which this occurs. Nor have the surveys clarified the nature of deformation in the impacted forearc. It is also unclear how the type of crust comprising the impacting feature affects the collision, and how this response might be a function of the size of the colliding feature.

The most extreme example of high-standing buoyant features to enter convergent margins is a continental margin. Such continental collisions, particularly in their early phases, show many similarities to oceanic convergence zones, and differ chiefly in the nature of the sediments accreted and the style of structures developed (Karig and others, 1987). Although continental margins carry thick sediment covers, it is not known how these interact with the forearc, or how the collision affects the distribution of deformation across the entire zone of convergence. There is great variety in the character of contemporary collision zones, which implies either an evolutionary sequence or differences in style or both.

One particularly important variety of collision involves the emplacement of an oceanic lithosphere slab 10 km thick or more (*i.e.* ophiolites) on a continental margin. Although usually couched in terms of "obduction", this process requires the ophiolite to have been an element in a forearc that converged on a subducting continental margin. The setting in which the ophiolitic lithosphere developed, what type of arc developed, and how the ophiolite came to be part of a forearc are all questions still being addressed. Ophiolites are often uplifted 10 km or more from their original setting, but much of that elevation occurs only long after emplacement.

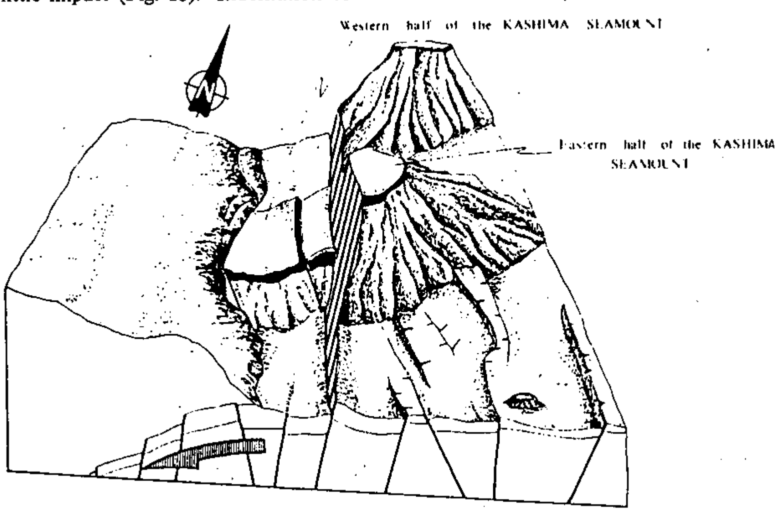


Figure 18. Faulting and subduction of a large seamount into the Japan trench, based on detailed surveys (Cadet and others, 1987b).

Understanding this complex vertical displacement history should provide much information about the mechanics of this type of collision.

The study of continental collisions and ophiolite emplacement will require an amphibious approach, with carefully integrated land and marine studies. For example, young ophiolites, like those obducted in Oman and Papua-New Guinea, lie along present continental margins, where the coastal plains and continental slope conceal the critical rear flank of the ophiolite exposures with the oceanic basinal floor. Consequently, both subaerial and marine drill holes between these end-points seem necessary to unravel their origin and evolution.

STRATEGY

Regional and Site-Specific High Resolution Geophysical Surveying

As ODP progresses toward a 1990's drilling philosophy whose major tenets will be deep penetration, complete sampling and the long-term use of clean holes as laboratories for monitoring the stress and deformation of the lithosphere, the following statement about the dual role of marine geophysics pinpointed by the COSOD I Report will become more important than ever before: "Future drilling must be part of a larger scientific program that includes... problem definition, site surveying, geophysical experimentation, and sample analyses. *Broad-scale problem definition* and *fine-scale site examination and selection* must precede drilling".

Broad-Scale Problem Definition

Since the advent of ocean drilling in the late 1960's, *regional geophysics surveys* have covered virtually every part of the marine environment accessible to surface ships, and recently satellite imaging has extended that control even further. New surveying techniques have been developed or adapted to academic scientific needs, most notably multichannel seismic reflection (MCS) profiling from the petroleum industry, multi-beam bathymetry (*i.e.*, SeaBeam) from the military and side-scan sonar (SeaMARC) imaging from various commercial sources (Fig. 19). In many parts of the oceans, reconnaissance is becoming a rationale of the past, although geophysical exploration will continue, particularly in high latitudes. However, even in some presently well-surveyed areas, such as along continental margins and over complex tectonic/topographic environments, like ridge crests, incomplete details of deep crustal structure and/or stratigraphy will require *combinations* of geophysical techniques (Fig. 19) to achieve a previously unparalleled level of geological characterization by remote sensing. Simply put, a deep hole to understand the evolution of the oceanic lithosphere will be incredibly expensive when compared with virtually any scale of geophysical effort designed to site that hole properly within a *known* geological environment. Consequently, a complete characterization of that environment prior to site selection is necessary to assure a sound scientific result at an acceptable cost.

Fine-Scale Site Examination and Selection

When definition of a regional environment is complete and site selection begins, *site-specific geophysical surveys* are crucial to assure: (1) accurate hole placement within that environment for the expressed scientific objectives; (2) suitable seafloor conditions both for placement of drilling-related structures (*i.e.* guide bases, re-entry cones, etc.) and for potentially long-term drilling operations; and (3) safety, particularly along continental margins where deep drilling carries with it the probability of encountering hydrocarbons with the attendant risks of equipment damage, blowouts and widespread pollution, even if a riser is being used. For site-specific surveying, combinations of geophysical tools will again be necessary, although they may be different from those employed for regional investigations. Consequently, future geophysical operations in support of ODP must develop a *two-tiered approach. Regional surveys must come first,* followed by a complete analysis of those results in light of other existing knowledge. *Site-specific surveys follow* only after the synthesis of all regional data is complete, and these must be conducted far enough in advance of any scheduled drilling so that the *best* site can be chosen for each set of lithosphere objectives.

SITE SURVEY DATA STANDARDS

TARGETS / TECHNIQUES	A	B	C	D	E	F	G
X = Vital (X) = Desirable (X)*= Desirable but may be required in some cases R = Vital for re-entry sites H = Required for high temperature environments	PALAEOENVIRONMENT (shallow penetration)	PASSIVE MARGINS	ACTIVE MARGINS	OCEAN CRUST (thick sediment cover)	OCEAN CRUST (<approx.400m.sed.cover)	BARE-ROCK DRILLING	ASEISMIC RIDGES, PLATEAUS & SEAMOUNTS
1.Deep penetration SCS	(X)	(X)	(X)	X or 3			(X)*
2.High resolution SCS	X	(X)	(X)	(X)	X	X	(X)
3.MCS & velocity determinations		X	X	X or 1			(X)*
4.Seismic data on cross lines	(X)	X	X	X	(X)	(X)	(X)*
5.Seismic refraction		(X)	(X)*	X	(X)	(X)	(X)*
6.3.5 Khz	X	(X)*	(X)*	(X)	(X)*	X	(X)
7.Multi-beam bathymetry	(X)*	(X)*	X or 8A	(X)	X or 8B	X	(X)* or 8A
8.Sidescan sonar: A - shallow	(X)*	(X)*	X or 7	(X)		(X)	(X)* or 7
B - deep-towed					X or 7	X	
9.Heat flow		(X)*	(X)*	(X)	(X), H	(X), H	(X)
10.Magnetics & gravity		(X)	(X)	(X)	(X)	X	(X)
11.Coring infotmation: A-palaeoenvironmental	X	(X)	(X)				
B-geotechnical		R	R	R	R,H	.X	R
12.Dredging					(X)*	(X)*	(X)*
13.Photography					(X)*	X	(X)
14.Current meter (for bottom shear)	(X)*	(X)*	(X)*				

Figure 19. Combinations of geological surveying techniques presently suitable or desirable for various drilling targets (from the JOIDES Journal, v. 12, N° 2, p. 75). Different arrays of tools will probably be used for regional vs. site-specific surveys, and new tools may also be in use by the 1991's.

Drilling Strategy

Physical State and Dynamic Processes

A global stress map is the ultimate objective of our state of stress characterization of the tectonic domains of oceanic lithosphere and can be best achieved in the framework of the drilling program by incremental growth over the life of the project. The progressive addition of stress measurements can be realized in a number of ways. First, we propose to take advantage of the logistic opportunities provided by other thematic interests, if a given hole is sited in a tectonic domain relevant to the development of the world stress map. This would mean that all those holes of interest would have to penetrate basement to a depth of 100 m or more and be thoroughly studied to measure physical properties and to determine if stress-induced wellbore breakouts are present. *If this was done, over a period of only a few years considerable data would accumulate that, when added to data available from oceanic earthquake focal mechanisms, should begin revealing the stress patterns associated with the forces that drive the plates.* Second, dedicated drilling efforts should be undertaken to define the state of stress within an oceanic plate. This would mean the development of a specific drilling strategy to characterize the state of stress along and across the plate in question. Detailed *in situ* stress measurements should be made to address problems such as plate-driving forces, the state of stress at mid-ocean spreading centers, transform faults and ridge/transform intersections, and deformational processes in convergent margins. Also, at selected sites, detailed physical property measurements, coupled with multi-offset, multi-azimuth vertical seismic profiling, would be important for the study of seismic structure and anisotropy. This would be especially useful at sites where ocean-bottom geophysical observatories might be stationed. Third, there is considerable interest in drilling deep holes (several km below the sediments) at various locations in the ocean crust. Physical property measurements in these holes would be extremely useful for calibrating regional geophysical data, and documenting the change in stress with depth in these holes could potentially distinguish between otherwise similar theoretical models of the shallow crust. Additionally, the deformational fabric of the samples exhumed from deeper wells would give important clues to *in situ* rheology.

To accomplish the objective of establishing ocean-bottom seismic observatories, we propose the goal of establishing over the next decade an optimized number of 25 sites, a minimum number being 11 sites. To meet this goal, work must begin to overcome a variety of technological problems. The question of data recovery from the observatories must obviously be considered very carefully. For instance, if the experiment must be routinely serviced to replace expendables and recover data, the data become very expensive. In many situations it will be more cost-effective to design the experiment to be maintenance-free over a period of years, with the data recovered in real time or near real time, for instance using the existing netwok of telecommunication cables. These and other data-return considerations must be evaluated very carefully in designing ocean bottom observatories. The other necessary technological development involves very broad-band sensors suitable for deep ocean borehole deployment. Such instruments presently exist for boreholes drilled on land. Adapting these to the oceanic environment should not present major difficulties (Worthington *et al.*, 1987).

The usefulness of other measurements should be carefully evaluated. These might include deployment of additional seismic instrumentation (arrays), observations of secular variations of gravity and tilt, and measurement of strain (for instance by very precisely measuring the distance between two neighboring observatories). Other observations could include passive electromagnetic measurements, pressure transducers and possibly environmental measurements. The oceanographic community should be widely consulted with regard to their needs. We recommend that these technological problems be addressed as soon as possible.

In the three-phase experimental program proposed above, only phase 2 deals with holes specifically dedicated to *in situ* stress measurements and to the geophysical observatories. In this respect, a program for the next decade could be divided into (1) mapping the state of stress in intraplate oceanic areas and establishing the geophysical observatories, and (2) studying the state of stress along plate boundaries. The intraplate program would need to drill holes in as many localities as possible. A typical hole should have between 100 and 200 m of penetration into the basement, requiring 5 to 8 days for drilling in the basement and 2 days for complete logging. The plate boundary program (see section on mid-oceanic ridges) would approximately require 6 holes per study area. Using the same time estimates as above, a given study would correspond to about one complete drilling leg. We recommend that one such a leg per year be dedicated to the study of plate boundary sites. Finally, in phase 1 of our program we simply make a pledge to use as many holes as possible penetrating the basement more than 100 m for stress measurements, and in phase 3, we wish, if there are several kilometer deep holes, that approximately one week is reserved in each hole for stress- and physical property-related experiments.

Rift Environments and Passive Continental Margins

The classification of passive margin types (volcanic, non-volcanic, and rift-transform) and the segmented character of most margins provide a favorable environment for focusing drilling-related passive-margin studies on only a few representative examples. Some basic guidelines can be established for the evaluation of potential margin segments as sites for focused studies :

1. Conjugate margin segments must be accessible for both geophysical and drilling-related studies.
2. Margins must contain substantial thicknesses of prerift, synrift and early postrift sedimentary sequences in order to establish timing and deposition patterns along and across the margins. Complete sedimentary records of the rifting process are crucial.
3. Samples of deeper crystalline material, hopefully from crust-mantle interface, and possible detachment faults must be within drill depth capabilities.
4. Typical oceanic crust and a well-defined seafloor spreading magnetic lineation pattern must exist adjacent to the margin.
5. Margins should be chosen because they have a distinctive multiple rift history or simple "single" rift history. They should not have a complicated postrift deformation history.
6. Regions of moderately thick postrift sedimentary sections (3-4 km) should be available within the same basin for establishing basin-wide biostratigraphic and paleoceanographic records needed to provide age calibration and establish the influences of paleoceanographic processes on the margin sedimentary record. There should be potential "standard-reference section" sites remote from major paleoceanographic gateways and sites adjacent to these gateways.
7. Margin segments where data are available from either the petroleum industry or past DSDP/ODP exploration should be incorporated where possible. ODP should build upon the successes of these previous drilling-related studies, rather than hoping that reconnaissance will always yield better results.

A basic premise of future passive margin drilling should be based on the need for deeper holes with thicker crustal records (sedimentary, igneous and/or metamorphic material) on conjugate pairs of margins. Most of the previous DSDP/ODP "deep" margin drill legs have been on sediment-starved margins and only on half of a conjugate pair. The other half has always had too much postrift sedimentary material or was too poorly surveyed. ODP must immediately start to drill margin sites with sedimentary thicknesses of 3-4 km. In the future, 4-6 km of penetration should be established as a feasible technological objective.

The need to acquire more samples of crystalline rock across passive margins, in a tectonic setting where they can be properly evaluated, will also require deep penetration capabilities. This would mean acquiring a reasonable synrift and prerift sedimentary section as well as substantial penetration (>1 km ?) of crystalline rock. Drilling on "volcanic" margins must include a suite of sites across the margin that penetrate the entire volcanic sequence and recover any intervening sedimentary material. These samples (igneous and sedimentary) are essential to evaluate the changes in petrologic and geochemical character, and paleoenvironment across the margin as well as determining age, paleomagnetic properties and rheologies. Hard-rock penetrations of 2-4 km are expected, and the number of desired drill sites on a typical margin (3-4) will necessitate a more efficient hard-rock penetration capability.

Furthermore, each of these deep drill sites should be carefully considered as a site for short- and long-term downhole experiments and monitoring. Hole stability will be crucial. The rock samples provide the best record of past stress regimes related to crustal deformation, while a stable hole provides an opportunity for studying the present stress regime.

An initial program of sampling the conjugate margins for existing rift margin drill legs (N.W. Africa, Galicia Bank, Goban Spur, Rockall Bank, Southern Africa Atlantic and Outer Vöring Plateau margins), with at least one non-volcanic and one volcanic margin, would require about 240 days of drilling (two 4-km sediment penetration sites) and 120 days of drilling (two 1-km sediment penetration and 2-km crystalline-rock penetration sites). A drilling program on a rift-transform margin needs to be established with at least one drill leg of 60 days. Finally, a site must be chosen where deep crustal rocks and distinctive major fault or crustal boundaries, such as the "S" reflector on the Galicia Bank or Northern Biscay margins, can be drilled. This would require at least one full leg (60 days) and perhaps two legs of drilling because sufficient synrift and prerift sections must be present in order to establish the kinematic history of such a boundary.

Mid-Oceanic Ridge System

In order to determine the state of stress and the physical properties of the oceanic lithosphere created along the axes of accretion, we envision a two-phase program.

1) The first phase involves a series of relatively shallow holes, single bit holes that would be 100 m to 200 m in depth, located in a number of relatively closely-spaced (<1 km to tens of km) arrays or transects along and across the strike of the ridge system at critical localities, including very young or zero age crust. The goal of this initial phase of the ridge drilling program would be designed to establish *in situ* stress at the critical tectonic domains that characterize the mid-oceanic ridge system : ridge-transform intersections ; along and across spreading centers with contrasting rates of opening (2 cm/yr to 16 cm/yr) and morphology (rift valley versus axial bulge) ; along transforms with variable slip rates and strike-slip geometries (single through-going fault vs. strands linked by relay zones) ; and at the tips of propagating ridges. The state of stress measurements would be augmented with detailed physical property and borehole studies which would help define the kinematics of brittle crustal deformation by determining fault orientation, the sense of motion of faults and the degree of block rotation. When these data are combined with towed instrument and submersible studies that have determined the structural fabric (fault orientation, relief, sense of motion and density) of the seafloor along with earthquake focal solutions, then the forces responsible for the deformation of oceanic lithosphere at shallow levels along the mid-oceanic ridge can be resolved. We estimate that several months of drilling time (2 to 3 legs) would be needed to determine the state of stress at the critical tectonic environments along the ridge systems.

2) The second phase in our program is to drill deep holes (2 to 3 km) within some of the arrays of shallow holes drilled during the first phases. These deep holes would provide a high-resolution vertical perspective. Their location would be based on the results of a decade-long commitment to understand the processes that govern the generation and evolution of oceanic lithosphere along the ridge, and this program would be linked to the objectives of Working Group 2. The sites would be located within critical tectonic environments that have already been the focus of extensive geological and geophysical investigations at a range of scales. These environments would represent natural laboratories in which investigations to define the dynamics of crustal accretion and deformation would be carried out. Data recovered through oriented samples and downhole measurements would yield critical information about the state of stress, the rheology of the rocks, the kinematics of crustal blocks and the geometry of faults at depth. It is premature to specify the number of holes needed to achieve our deep crustal objectives because the global program to study the ridge system is just beginning. We can, however, foresee that at least two 3000 m deep holes will be needed, one each at the fast and slow end of the accretionary rate spectrum.

Convergent Margins

The great length of subducting plate margins and finite drilling resources demand that very carefully chosen examples be selected from the spectrum of subduction responses for drilling. To accomplish the highest priority objective of elucidating flow patterns of material through the forearc, a drilling strategy must be based on a dual approach : (1) the time-space distribution of material in forearcs must be determined to constrain geometries and kinematics of material, and (2) the processes operating in the forearc must be approached by the *in situ* measurement of physical, chemical and geological parameters.

This philosophy translates into a two-phase drilling program of a number of intermediate depth holes (0.5-1 km), generally in the transects across the forearc examples chosen, followed by several much deeper holes (2-4 km) into the forearc. Perhaps a total of 5 forearc examples would be sufficient to outline the range of behavior, but holes in some of the forearcs presently under study would reduce this number. Furthermore, each transect could be treated as a complete experiment and be tied with the objectives of Working Group 3. Although the identification of examples must await extensive geophysical surveying, the strategy for a typical example can be suggested.

1) On the basis of past drilling experience, phase 1 corresponds to about 5 drill sites, with holes of 0.5-1 km penetration across each forearc, to outline the general framework. At some of these sites, for instance where slumping or complex, near-surface behavior is suspected, arrays of HPC holes will be necessary. Although the primary purpose of these holes is to develop the geologic record, as much information concerning the *in situ* state should be obtained by logging and *in situ* techniques. This will require that some less stable holes have re-entry capability and surface casing. Such holes are now and soon will be capable of being drilled and clearly are necessary to provide geological and technical guidance for the second phase of drilling. Approximately 12 months of drill time will be necessary for this phase, assuming 5 transects of 5 sites each.

2) Phase 2 corresponds to several (2 to 3) very deep holes (2 to 4 km), not only in the toe of the forearc but several tens of kilometers further to the rear. Some of these holes will require pipe strings 9 km or more in length. Not only will these re-entry holes have to be partly cased, but possibly also have risers or some method by which fluid pressures can be controlled. Extensive experimentation and *in situ* measurements would be a very important component of each such hole, including not only logging and geotechnical probes but also vertical and offset seismic experiments. If 4 such sets

of holes were drilled, each of which would require at least 2 months to complete, phase 2 would require 8 months of drilling.

Linkages of WG 4 with the Other COSOD II Working Groups

A number of the major objectives identified by WG 4 are compatible with the scientific goals identified by some of the other COSOD II working groups. Such linkages are important to identify because broad-scale problem definition and fine-scale site examination and selection can be combined for a number of scientific objectives, thereby optimizing time and resources. For example, our convergent margin objective is to elucidate flow patterns of material through the forearc. Many of the fundamental processes which bear on this question, like the mechanisms and paths of water flow and the nature of geochemical fluxes, are processes that are central to the interests of WG 3. Another high priority of WG 4 is to establish the state of stress and the deformation history of oceanic lithosphere created along the axis of Mid-Oceanic Ridge and intervening transform faults. This objective deals with definition of the mechanical processes responsible for the modification of the igneous architecture created by the emplacement of magma at shallow levels along the ridge axis. A resolution of these magmatic processes is a central focus of WG 2 and it would be folly to design a drilling strategy to investigate the objectives of WG 4 and 2 in isolation.

In terms of logistical considerations, the highest priority WG 4 objective, which is to establish a global definition of the state of stress in oceanic lithosphere, is compatible with the global sampling requirements of WG 1 and 5. The objectives of WG 1 and 5 will take the ship to remote localities and involve long transits across ocean basins. The logistical ramifications of this component of the drilling program will make it possible to make stress measurements at key, but remote localities within various plates.

Linkages of WG 4 with Other Major Research Initiatives in the Earth Sciences

There are a number of international research initiatives that are in progress, or are planned, that have goals compatible with our high priority objectives. First, our proposal to determine the state of stress and physical properties of oceanic lithosphere will complement and enhance the ongoing project to create a world stress map that is being compiled under the auspices of the *Inter-Union Commission of the Lithosphere*. Second, our proposal to create ocean bottom geophysical observatories at a few key localities within oceanic lithosphere will provide both short- and long-period seismic information that is presently unavailable and represents a necessary and needed complement to the land-based *Global Seismographic Network*. Third, our proposal to establish the state of stress and deformation history of rock bodies at diagnostic tectonic environments along and across the Mid-Oceanic Ridge system would provide results that are central to a developing international research initiative to study the global ridge system. This program, called *RIDGE (Ridge InterDisciplinary Global Experiment)*, has a unifying goal to understand the physical, chemical and geological causes and consequences of energy transfer within the global ridge system through time and space. Fourth, the initial plans for an integrated and international program to investigate the origin and evolution of passive continental margins are underway. Such a program will involve sophisticated and co-ordinated geological and geophysical investigations designed to define the syn- and postrift subsidence history of passive margins. Clearly, sampling of passive margins is essential to this program and consistent with our high priority objective to understand the thermal and structural evolution of the rifted margin tectonic domain.

FUTURE TECHNOLOGICAL DEVELOPMENTS

The objectives outlined in the preceding sections of this chapter can only be satisfactorily answered with direct sampling and *in situ* measurements. The successful resolution of these objectives then rests on our ability to implement a drilling program in a timely, successful and cost-effective fashion. Many of the WG 4 goals can only be answered if deep (2-4 km) holes can be routinely drilled. Such an effort is only feasible if holes can be drilled at relatively rapid rates (30 m/day) into the crust. Many of our drilling objectives are located in terrains with physical properties (*i.e.* fragmented basaltic basement ; unstable sedimentary assemblages) that have made drilling difficult in the past. In order to insure safety in terms of environmental concerns and to maximize the scientific return, it will be necessary to control fluid pressure (riser capability) in the holes located along the passive and active margins.

A drill hole into oceanic lithosphere represents an invaluable probe and, therefore, every attempt must be made to maintain high recovery rates of cored material. Furthermore, because a drill hole provides an opportunity to sample a much larger volume by providing a pathway for *in situ* measurements, it is very important that an effort is made to support and develop state-of-the-art downhole measurement capability.

CONCLUSIONS

In order to move toward a comprehensive physical understanding of solid Earth processes, we need to improve the definition of the internal structure of the Earth, establish the state of stress in the upper part of the lithosphere, and resolve the dynamics and kinematics of phenomena that characterize the edges of plates. In the preceding sections of this chapter, we have outlined the rationale for a drilling strategy that will contribute to a better understanding of these solid Earth processes. We propose to :

1. Emplace geophysical/seismological observatories within the interior of oceanic plates, thereby contributing to a better definition of deep Earth structure.
2. Carry out a comprehensive program to measure the state of stress within oceanic lithosphere to resolve the forces which drive and deform plates.
3. Implement a sampling and *in situ* measurement program in holes sited along conjugate rifted margins, along and across the oceanic ridge system, and along the forearc of convergent margins in order to resolve the deformation history of these tectonic environments.

Our proposal to establish long-term geophysical/seismological observatories in a few holes located in the interior of large oceanic plates recognizes a need to enlarge and improve the sampling of the Global Seismographic Network. These observatories would be located far from the contaminating effects of anomalous lithosphere and the long- and short-period seismic data obtained at these stations will greatly enhance tomographic images of the interior of the Earth, providing new and fundamental insights about the causative processes that shape the Earth's surface. This focus of our proposed program cannot be implemented until certain technological problems (*i.e.* data transfer and retrieval, instrument development) are solved. A commitment should be made now to the solution of these developmental problems so that these observatories can be established during an early phase of the COSOD II drilling program.

Our proposed global definition of the state of stress in the oceanic lithosphere will contribute to our understanding of the dynamics of the oceanic lithosphere and provide constraints needed to test physical models about the forces which act on plates. The technology needed to carry out these measurements is available and the measurements can be made at relatively shallow crustal depths (100-200 m) with a relatively small investment in time and resources (*i.e.* single bit hole). This program to elucidate the forces acting on plates involves a global characterization of the state of stress within the oceanic lithosphere as well as transects to measure stress and physico-chemical properties at selected localities along the deforming margins of plates. With the necessary technology in hand, and given the logistical implications of a global sampling program, we propose that this first phase of stress characterization be implemented immediately and be integrated with the present phase drilling. A global representation of the state of stress is a sampling problem and, therefore, stress measurements should be routinely made in all holes that penetrate basement in localities of interest. Such a sampling strategy should carry into and through the COSOD II phase drilling. The second component of our state of stress program - multiple measurements at critical localities along plate boundaries - can be implemented during COSOD II and will be integrated with our program to investigate the deformation history of plate boundary environments.

The sediments and the underlying crystalline rocks of passive margins contain the information needed to unravel the syn- and postrift processes of margin devlopment. Because the detailed history of margin evolution is contained in the sedimentary record of a given margin, a basic guideline for future drilling during COSOD II is a need for deep holes into crystalline basement overlain by thick sedimentary records on conjugate pairs of margins. This means that holes 4-6 km in depth must be a feasible technological objective. Three different classes of passive margins have been identified (non-volcanic, volcanic, and rift-transform) and the evolutionary path that each one follows will require a major commitment. Clearly, passive margin studies represent a long-term endeavor incorporating observational constraints, theoretical studies and drilling (sampling and *in situ* measurements). A two-phase drilling strategy is envisioned where certain objectives could be reached initially with 3-4 km deep holes followed in the future with 4-6 km penetration when technological needs are realized.

The world oceanic ridge system is characterized by very high rates of relative motion (a few centimeters to 16 cm/yr). Little is known, however, about the complex and interlinked processes of magmatism, deformation and lithospheric evolution that operate along and proximal to this dynamic interface. The oceanic lithosphere created along the ridge axis thickens continually away from the ridge and represents a mechanically strong boundary layer that overlies weaker, ductile mantle. The newly formed and thickening lithosphere will be subjected to a variety of stresses and it will be the resolution of these stresses coupled with the mechanical properties of the rocks comprising the lithosphere that will control the patterns and styles of deformation. We propose a two-phase program to determine the dynamic aspects of the ridge system. The first phase involves a series of relatively shallow holes, 100 m to 200 m in depth, located along and across the strike of the ridge at diagnostic localities (*e.g.* ridge-transform intersections, ridges and transforms with contrasting rates of opening, tips of propagating ridges). This first phase would be implemented during the first half of the COSOD II program and would augment our global state of stress objective. The second phase of our ridge program would be to drill deep holes (2 to 3 km) within the arrays of shallow holes drilled during the first phase. These deep holes would provide information about the state of stress, rheology of these rocks, the kinematics of crustal blocks, and the geometry of faults at depth.

In general terms, the formation of continents through time and their internal architecture are products of processes that characterize convergent plate boundaries. Very important components of this system are the processes associated with the flow of material within the accretionary prisms of the forearc. Accretionary prisms constitute a natural laboratory in which porous sediments are deformed and consolidated under differential stress. A scientific program to explore the variations in trajectories of material within forearcs must use a system approach with carefully integrated elements undertaken in appropriate sequences. As such, the location of drilling transects must be preceded by extensive geophysical investigations that will characterize contrasting accretionary environments at a regional scale. We envision a two-phase drilling program to resolve flow patterns of material through the forearc. The first phase, which could be implemented during the first portion of the COSOD II program, would involve transects of approximately 5 holes, 0.5-1 km deep, across the toe of forearcs representative of the range of accretionary prism environments (5 transects). The second phase, designed to investigate deep-seated deformational mechanisms, requires a few holes, 2-4 km in depth, within the forearcs of interest. These objectives will be technologically demanding, requiring long drill strings (9 km) and control of fluid pressures in the hole. This second phase would be carried out during the later half of COSOD II drilling.

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Program EPOC : Evolutionary Processes in Oceanic Communities

Prepared by WORKING GROUP 5 (see p. 10)

ABSTRACT

Preamble. Two decades of scientific ocean drilling have significantly advanced our understanding of the evolutionary history of the oceanic biota and provided a basic appreciation of the interactive feedback between the biosphere and geosphere on various time scales. Crucial questions of fundamental paleobiological importance have been identified in the course of this drilling; however, these can only be addressed by a new generation of scientific ocean drilling, employing high-resolution, stratigraphic and investigative techniques combined with improved quality and quantity of drilled materials. Furthering our understanding of significant problems in macro- and microevolution, such as speciation, extinction, and evolutionary ecology requires detailed, quantitative data with the unique properties provided only by deep sea drilling cores, namely :
- closely spaced samples with abundant, well-preserved fossils,
- good time resolution and correlation, and
- wide geographic distribution of coeval samples.

The specific models to be tested and the stratigraphic intervals and geographic areas most suitable for such tests are outlined in the section : Scientific Rationale for Program EPOC. To realize these ambitious goals, a large group of scientists gathered at COSOD II has recommended that scientific ocean drilling in the next decade be focused on the following three major EPOC objectives.

Epoc Objective 1 : Evolutionary Global Ocean Drilling Array. An understanding of evolutionary processes in the oceans demands detailed temporal and widespread geographic sampling of oceanic sediments. To document the tempo and pattern of evolution requires a global array of sites. This array should span all biogeographic provinces in all ocean basins so that the entire evolutionary history of the late Cenozoic can be analysed. The chief objectives for this phase of the program will be focused on :
- patterns and modes of speciation and diversification and their morphometric quantification,
- the geography of these processes and their relationship to physical-chemical factors.

These quantitative data will help us calibrate the normal rates of speciation and extinction as well as their synchroneity or diachroneity. In addition to these evolutionary objectives, samples collected for this global array will contribute to our understanding of paleoenvironmental, geochemical, and paleomagnetic processes.

Epoc Objective 2 : End Cretaceous Extinctions and Early Cenozoic Recovery. The end Cretaceous and early Tertiary encompasses an extraordinary and still controversial interval in the evolutionary history of the oceanic biota. It includes :
- normal background evolution on a warm Earth (in marked contrast to the Neogene),
- one of the largest mass extinctions in the history of life, and
- post-extinction recovery of the biota during the succeeding 10 to 20 million years.

Investigation of the oceanic fossil record from this interval is of great importance since it permits study of evolutionary patterns and processes in a system that lacks strong latitudinal and depth gradients in temperature and has witnessed the nearly complete collapse of oceanic ecosystems and their subsequent evolutionary rebound in a biotically rarefied environment. Some of the most important questions we can ask of this interval include :
- To what extent does the evolutionary behavior of various groups of organisms prior to the K/T (Cretaceous/Tertiary) boundary permit us to predict their success or failure during the mass extinction ?
- How gradual or sudden were the extinctions ?
- How selective were the extinctions toward taxonomic, ecologic, and biogeographic groups ?
- What were the dominant patterns of taxonomic and morphologic evolution that determined the nature and composition of the biota during the post-extinction recovery ?
- What were the similarities of other extinction events to the major K/T boundary mass-extinction ?

Answers to, or insights into, these questions will promote our understanding of the causes of extinction events, the role of terrestrial and/or extraterrestrial perturbations in the history of life, the nature of radiations in biotically rarefied environments, and the changes in dominance and the repetitive diversification of taxonomic groups.

Epoc Objective 3 : Origins and Early Radiations of Modern Microfossil Groups. The successive rise to dominance of calcareous and siliceous phytoplankton and calcareous zooplankton groups from the Late Jurassic onward has profoundly influenced global oceanic sedimentation patterns. Large-scale fluctuations of skeletal production by these groups may have led to changes in the global cycling of major elements and may be correlated with repeated increases and decreases of morphological variation. These radiation events may be the only opportunity to study the forcing of global chemistry and climate by biotic evolution. Questions to be addressed include :
- What is the temporal and geographic variability of skeletal production of major oceanic microfossil groups ?
- How is this variability correlated with taxonomic diversification and extinction ?
- To what extent are evolutionary patterns in the plankton coupled to patterns in other oceanic communities, such as the microbenthos ?
- How are the successions of microplankton and microbenthos related to geography, fertility, climate, and circulation of the oceans ?
- What are the feedback mechanisms between radiation of these major biotic systems and global chemical environments ?

Implementation of Program Epoc. **The drilling requirements for Program EPOC are continuously recovered core sequences from multiply-drilled sites that represent global coverage. In the absence of any comprehensive compilation of currently available drill sections (with adequate core recovery, magnetic stratigraphy and microfossil contents) only a very rough estimate of the number of additional sites to be drilled is possible. For instance, out of 120 DSDP sites drilled since the advent of HPC, 30 sites (_i.e._ 25%) fulfill the stratigraphic requirements (but not always the geographic ones) necessary for the studies proposed here, although that proportion may increase dramatically for legs specifically designed for such purposes (_e.g._ Leg 90). No estimates are currently available for the approximately 100 ODP sites drilled so far. We estimate that, at the end of the currently planned Indian and Pacific Ocean drilling, an adequately high geographic resolution in the late Cenozoic could be achieved with approximately an additional 100 continuously recovered sites for planktonic groups (first priority) and an additional 100 sites for benthic groups (second priority), spread over all ocean basins, and a wider-spaced global array of about an additional 30 sites (for all groups, first priority) back into Cretaceous and Jurassic crustal segments. Major scientific advances on the proposed topics can thus be achieved in about four years of drilling. At least half of the recovered cores will also serve the high priority targets of Working Group 1.**

To achieve the thematically defined goals, a more efficient procedure than currently available in the JOIDES structure will have to be implemented, which will promote the development of specific site proposals designed to address thematically defined drilling programs. In addition, a significant technological improvement must be made to greatly enhance core recovery of layered hard and soft sediment sequences frequently encountered in Eocene and older rocks.

SCIENTIFIC RATIONALE FOR PROGRAM EPOC

In the following sections we outline the scientific rationale of the EPOC objectives, focusing on specific problems that require such data and that can be uniquely investigated with scientific ocean drilling.

Parts of this chapter are based on a report from a workshop "The Future of Ocean Drilling" held in Gwatt, Switzerland, 18-20 March 1987, organised by the ESF Consortium for Ocean Drilling (ECOD), and a report from a workshop "Paleomagnetic Objectives for the Ocean Drilling Program" held at the University of California, Davis, 4-6 September 1986, sponsored by JOI/USSAC and organized by K. L. Verosub, M. Steiner and N. H. Opdyke. We also acknowledge numerous contributions to various parts of this chapter by scientist attending the COSOD II Conference.

For stratigraphic terminology and geological timescale refer to Figure 1.

EVOLUTIONARY MODELS

Patterns of Speciation

There has been considerable discussion and debate within the last few decades about patterns and processes of speciation over geologic time. Yet there is a dearth of well-documented case histories to test and evaluate alternative hypotheses (_e.g._ punctuated equilibrium and phyletic gradualism). Because of the ease of collecting statistically large samples of individuals from closely spaced successive horizons in relatively complete sequences over broad geographic ranges, marine microfossils offer the best material for study. Such palaeobiologically oriented research has just begun (_e.g._ Malmgren and Kennett, 1981 ; Lazarus, 1983 ; Malmgren _et al._, 1984 ; Banner and Lowry, 1985 ; Whatley, 1985) and promises to be one of the most exciting areas of future scientific advance. Important questions that need to be addressed with reference to a number of groups (_e.g._ foraminifera, coccoliths, radiolaria, diatoms, dinoflagellates and ostracodes) include the following: What is the relative incidence of alternative patterns of speciation in inshore vs. pelagic and benthic vs. planktonic groups ? Do speciation events predominantly involve continuous transformation of an ancestor into a descendant within a lineage (anagenesis) or do they consist of the branching off of descendant species which can coexist with the ancestor (cladogenesis) ? Is the phenomenon termed "punctuated gradualism" by Malmgren _et al._ (1984), involving rapidly evolving anagenetic morphological trends within given lineages, of common occurrence ? Does long-term morphological stasis (_i.e._ lack of directional change) within species involve frequent oscillations (Stanley and Yang, 1987) or tightly bounded stability ? Does morphological variability at identified speciation events increase relative to the variability established during preceding intervals of stasis ? There is a critical need for more quantitative data to determine the extent and character of morphological change within lineages. Geographic control needs to be extensive in order to eliminate the possibility that successional replacement of species involves migration rather than _in situ_ evolution ; it follows that the more comprehensive the geographic range of drilling sites, the better.

Geography of Speciation

The global oceanic record of planktonic and benthic microfossils provides a means of testing models for the geographic basis of speciation. The principal models are allopatry (geographically isolated peripheral populations give rise to new species), sympatry (new species arise within the range of existing species) and parapatry (new species diverge along an environmental gradient). The relative role these models play in oceanic systems is fundamentally a historical question, amenable to tests in the fossil record. Quantitative chronological documentation of morphologic changes in complete fossil records at sites selected for this purpose (_e.g._ Keigwin, 1982) are required. For example, plankton species have been suggested to arise from populations isolated in marginal environments (Emiliani, 1982) ; they might also arise in separate water masses or in the transitional regions between water masses (McGowan, 1974). Deep ocean drilling is playing an important role by providing the material necessary to resolve this and other problems. Does allopatry chiefly occur in marginal marine environments, isolated basins, isolated water masses, or in transitional regions between water masses ? Does sympatric speciation occur throughout the range or in the centers of distribution ? Along what physico-chemical gradients does parapatry occur ? Of what temporal persistence is it ?

A second set of questions deals with variations in geographic aspects of speciation between major ecosystems. Does the geography of speciation in plankton resemble that in the benthos ? More specifically, are these modes different for different plankton groups and benthic groups (_e.g._ zooplankton vs. phytoplankton, siliceous vs. calcareous taxa) ? How do geographic boundaries or barriers differ between these groups ?

Because deep ocean systems (and others that might be suitably sampled, _i.e._ shelf or shallow carbonate settings) differ in their distribution through time, a drilling program to address these problems must include appropriately dispersed geographic sites (although the same sites may serve other purposes).

A recent proposal that the occurrence of high-latitude oceanic species may have preceded their appearance in lower latitudes is a significant challenge to the view that the tropics have been the important centers for evolution (Zinsmeister and Feldmann, 1984 ; Marincovich _et al._, 1985 ; Crame, 1987). A high-latitude origin and subsequent mid-latitude migration has also been suggested for terrestrial biota (Hickey _et al._, 1983),

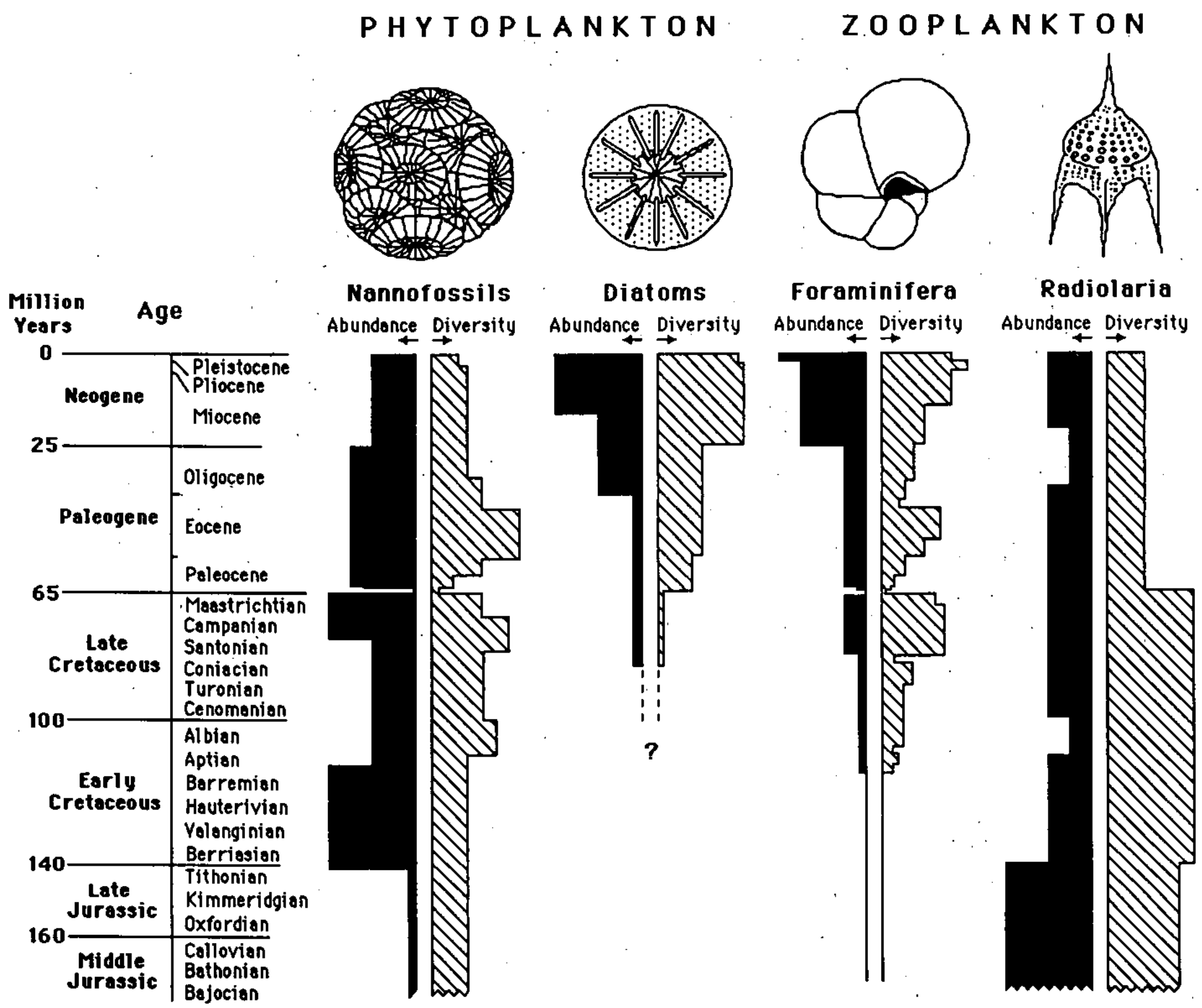

Figure 1. Geological time scale with generalized abundance and taxonomic diversity of major skeletonized marine plankton groups (plants and animals) normalized to known maxima in each group. Compiled from various sources (Bolli *et al.*, 1985; Bramlette, 1958; Haq, 1973; Kennett, 1982; Tappan and Loeblich, 1973; Thierstein and Woodward, 1981; Wei and Kennett, 1986).

although this has recently been challenged (Spicer *et al.*, 1987). Unfortunately, the high-latitude record is poorly documented despite its importance in testing significant paleobiologic theories. In particular, the circumpolar Antarctic current system and the central Arctic Basin, with their present-day chemical-physical characteristics, represent the youngest oceanic environments on earth. The strong contrast between seasonally extreme fluctuations in the physico-chemical environment of polar oceans versus the more stable conditions prevalent in tropical waters also suggests that the forcing factors of evolution in polar regions may be quite different. Depth transects from shallow to deep water on high-latitude continental margins will provide much of the information needed to address these questions. In addition, the technology is now available that will permit long-core recovery in ice-covered oceans. An extremely important contribution to paleobiological research will be a program of high-latitude Arctic drilling.

Relative Importance of Biotic and Abiotic (Physicochemical) Factors in Evolution

One of the major questions of evolutionary biology is the extent to which rates of evolution are determined by biotic interactions such as competition and predation (Darwin's "struggle for existence") and/or by changes in the physical environment. The first possibility, also known as the *Red Queen Model*, postulates that rates of extinction and speciation, for example, are a constant, independent of the age of a species (biologic time) but not independent of geologic time (Van Valen, 1973), or in other words: What one species gains in a community, another must lose. The second possibility, dubbed the *Stationary Model*, predicts that rates of evolution require changes in the physical environment (Stenseth and Maynard Smith, 1984). Several recent studies have demonstrated the feasibility of using the microplankton record for tests of such models (Hoffman and Kitchell, 1984; Wei and Kennett, 1986; Kitchell, 1987). Much more testing is possible, given improved paleoenvironmental data, such as oxygen and carbon isotopes and geochemistry of shell material (*e.g.* Boyle and Keigwin, 1982). Comparative studies will be especially important, such as those between regions with different environmental characteristics (tropical and polar seas, the pelagic realm and shallow shelf, etc.), to determine the extent of significant differences in the biotic response to observed environmental changes.

Heterochrony

Heterochrony is especially important as a developmental means of generating novel morphological types within evolutionary lineages. Heterochrony involves the study of the relationship between the developmental and growth history of individual organisms (ontogeny) and the evolution of a phyletic succession of species (phylogeny) (McNamara, 1986). As a consequence of change in the timing and rate of development of characters, probably under the control of regulatory genes operating early in ontogeny (*e.g.* Schweitzer *et al.*, 1986), the adults of some descendant species resemble the juveniles of their identified ancestors (paedomorphosis) whereas in other instances the reverse is true (peramorphosis). The incidence and character of heterochrony in the fossil record, particularly in microfossils with accretionary growth such as foraminifera (Huang, 1981 ; Brummer *et al.*, 1986), has the potential to make substantive contributions to our understanding of evolutionary processes. With an adequate knowledge of the growth history of individuals within populations, heterochronic processes, involving variations in the rate of development of particular morphological features with respect to total life history, may be quantitatively documented.

Relative Role of Terrestrial and Extraterrestrial Evolutionary Control

Terrestrial changes that may be important as proximate causes of evolution include climatic changes, sea-level fluctuations, oceanic anoxia, and salinity changes ; volcanism is also considered a potentially important terrestrial forcing function of these changes (Officer *et al.*, 1987). Extraterrestrial events that might result in evolutionary changes include, most importantly, major meteorite or cometary impacts but also Milankovitch cycles. Comparatively little is rigorously understood about the relative importance of terrestrial versus extraterrestrial events in causing environmental change and subsequent extinction and evolutionary change, even though there is a large speculative literature. Mass extinction intervals, during which large numbers of ecologically and genetically diverse species disappear from the Earth, have been variously interpreted as geologically instantaneous, step-wise (short-term), or gradational. Extraterrestrial forcing, such as by meteorite impact, is favored for some extinction events. But not all extraterrestrial impacts have resulted in extinctions. For example, the North American tektite field (34.6 My), related to an impacting object of approximately 3 km in diameter, is not correlated to any extinctions of planktonic foraminifera, although there were extensive within-species (micro-evolutionary) changes.

Important developments in the future will include quantitative evolutionary models that make unique predictions for terrestrial vs. extraterrestrial factors, and systematic surveys over long time intervals for these factors and their associated biotic changes. It should, for example, be established to what extent indicators of impacts are globally coupled to evolutionary events or whether they are sometimes confined to particular ocean basins or climatic zones and thus not necessarily distinct from the predictions based on other factors, such as explosive volcanism. The research agenda required to distinguish the kinds and importance of the various factors must include systematic, high-resolution collection of oceanwide occurrence data for species in order to catalogue the precise temporal and geographic nature of the biotic changes preserved.

Selectivity and Episodicity of Extinction Events

At the present time, the distinction between extinction events and the "background" extinction of normal times is rather arbitrary (Flessa *et al.*, 1986). Too little is yet known about variation in extinction rates over long intervals of time and about durations, intensities, patterns, and geographic manifestations of various extinction events that have been recognized (see below). Detailed description and characterization of various events is essential for understanding how gradual or abrupt extinction events were and whether extinction events represent a class of evolutionary phenomena distinct from background extinction (Jablonski, 1986 ; Kitchell *et al.*, 1986).

The most promising research program on extinction phenomena will likely involve the determination of "selectivity" : how non-random are major extinction events with respect to taxon type, habitat, biogeography, and ecology ? To understand, and not merely describe, extinction events, it is necessary to determine if and when such events are most pronounced in tropical biota (perhaps implying climatic refrigeration), in shelf biota (perhaps implying sea-level forcing), in pelagic biota (perhaps implying impact or volcanism), in particular biogeographic provinces (perhaps implying local causes), or in biota sharing similar ecological or life history characters. With a systematic inventory of the kinds of biotic changes, and their patterns of taxonomic, character, and geographic selectivity, it would be possible to recognize repetitive patterns that correlate with sedimentary and/or geochemical variables tied to specific kinds of physical change.

In addition to the search for causes and constraints of extinction, investigations should be conducted of the biotic effects of Milankovitch cycles. Climatic changes linked to these cycles can cause variations in ocean temperatures, deep circulation, surface productivity, etc. which may affect relative abundances and morphologic variability of oceanic species.

Raup and Sepkoski (1984, 1986) have argued that extinction events over the last quarter billion years display a statistical periodicity of 26 Ma (Fig. 2). This suggests that the events are serially dependent and may share a common ultimate cause that has clock-like behavior. Detailed comparative studies of the patterns of extinction within events and of their taxonomic selectivity and geographic extent are essential to determine if the periodic extinction events are sufficiently dissimilar to falsify the suggestion of common cause.

RADIATION EVENTS

Rise to Dominance of Plankton Groups

The successive rise to dominance of the major groups of shelled plankton over the past 200 million years is only very crudely known (Fig. 1). Deep-sea sediments known from the Paleozoic through Upper Jurassic consist exclusively of shales and cherts. Only since the latest Jurassic has carbonate been a

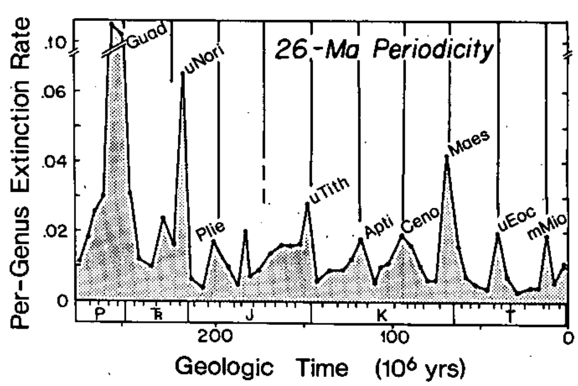

Figure 2. Intensity of generic extinction in the oceans from the mid-Permian to Recent, showing the purported 26 Ma periodicity in mass extinctions. Intensity is measured as the per-genus rate of extinction (= probability of extinction) in units of extinctions per genus per million years. The peaks in the time series correspond to documented major mass extinctions and more minor extinction events, as well as presumed extinction events. Modified from Sepkoski (1986).

major component of pelagic sediments. This represents a major physical change driven solely by biotic evolution, since the transition is coincident with a major increase in mass and taxonomic diversity of calcareous nannofossils and other groups which must have affected the oceanic cycling of carbon. This transition is documented in ophiolite sequences on land and in the Atlantic Ocean, but, because of inadequacies of current drilling techniques, not yet in the Pacific Ocean. The development of an adequate chronology for this interval and the recovery of continuous Jurassic deep-sea sediment cores are most urgent future tasks.

Planktonic foraminifera contributed little to the oceanic biomass from the Middle Jurassic to the Barremian. By the late Cretaceous, they contributed around 2% (by weight) to well-preserved carbonate oozes ; in the Paleogene their proportion increased to about 5-20% and in the Neogene to over 30% (up to 50% today). Is this long-term increase a real evolutionary enhancement of foraminiferal production, or might it simply reflect a decrease in nannoplankton carbonate production ? If real, is it correlated with changes of particular environmental parameters, such as productivity, temperature, water structure, etc., or is it occurring independently of environmental variability ? What are the consequences for the cycling of carbonate and carbon in the oceans ? Unfortunately, these changes are very poorly documented because most existing deep-sea drill holes are from relatively deep sites where the foraminiferal abundances are determined mostly by dissolution rather than supply. Shallow, well-preserved carbonate sequences are necessary to investigate the relationship between this major evolutionary radiation and global environmental changes.

The accumulation of siliceous biogenic sediments, mostly diatoms (which first appeared in the Jurassic), was depressed in high southern latitudes during the Paleogene but then increased dramatically in the late Neogene (Brewster, 1980). By contrast, the scarce Arctic sediment record to date of Upper Cretaceous-Paleogene sediments is one of biogenic siliceous supply (Kitchell and Clark, 1982). Peaks of opaline silica deposition on the deep ocean floor have been identified in the central Pacific in the Eocene and the Upper Miocene. What are the controls on these global shifts ? Are such supply changes related to taxonomic diversity changes ? Are they driven by productivity, seasonality or temperature, or are they intrinsic to the taxonomic group ?

At present, little is understood about the origin of the deep-sea and high-latitude benthic faunas. Were the high latitudes the site of origin of the deep-sea fauna or did it evolve *in situ* ? Latitudinal core transects with detailed correlation and magnetostratigraphy will be necessary to resolve this and related problems.

Radiations Following Extinction Events

Extinction events reduce diversity of plankton and benthos to varying degrees. It is of importance, then, to understand how diversity rebounds following such declines, particularly when these declines are selective. Diversification, as a process, is poorly understood in general and not at all for oceanic plankton and benthos (Fig. 3). Complete, magnetostratigraphically dated records following extinction events (see below) would provide appropriate material for study. Questions that need to be addressed include : What are the rates of diversification ? Do rates become high immediately after extinction events, or are there substantial lags ? Are rates uniformly high during radiations, or are there marked fluctuations through time ? What taxonomic groups contribute to diversification ? Do diversification rates vary in different biogeographic regions ? How does diversification correlate with measurable environmental factors ? Is there an "equilibrium" diversity beyond which diversification cannot progress ? Which species (generalists or surviving specialists) are more apt to diversify immediately after an extinction event ? Do all surviving species maintain previous ecological characteristics or do some move into new niches ? And how do post-extinction event radiations compare in rate and structure to evolutionary radiations occurring during "normal" times between events (*e.g.* lower Campanian radiation of planktonic foraminifera and radiolarians) ? Answers to these and other questions should provide for the formulation and testing of generalizable hypotheses.

Within-Group Diversification

Repetitive diversification and the appearance of similar morphologies at different geologic times within groups of plankton have been recognized (Cifelli, 1969 ; Lipps, 1970, 1986 ; Leckie, 1987). This diversification is commonly referred to as iterative evolution (the repeated rise of similar morphologies). Because "iterative evolution" has other implications, we use the descriptive term "repeated

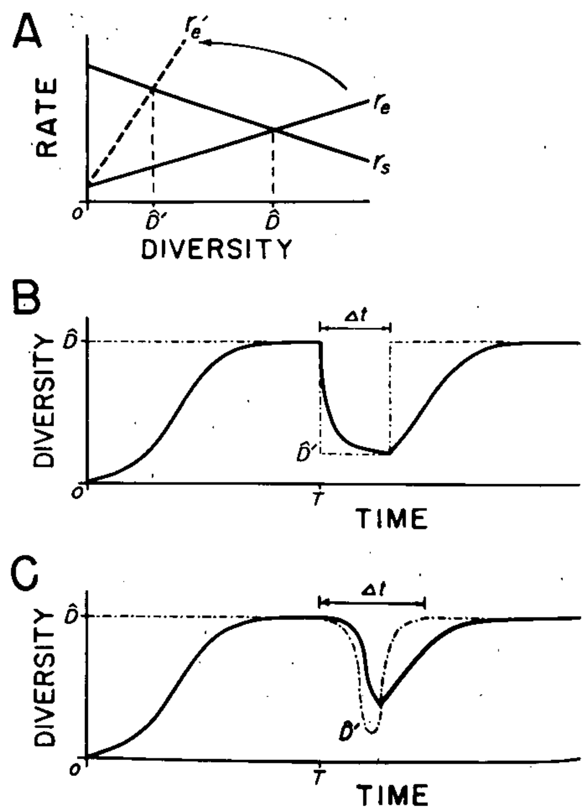

Figure 3. A logistic model of diversification showing the expected evolutionary radiation (rebound) following a mass extinction. A. A logistic system is produced by linearly declining speciation rate (r_s) and/or increasing extinction rate (r_e), which intersect at some equilibrium diversity ($\hat{D}$). A mass extinction can be considered a temporary increase in the slope of the extinction function to r_e', redefining the equilibrium to $\hat{D}'$. B. After a simple decline in $\hat{D}'$ for an interval Δt, diversity immediately rebounds, following the same sigmoidal trajectory as in the initially diversifying system. Note that if diversity were to decline to some small fraction of $\hat{D}$, there would be a temporary "exponential" lag, during which diversification would proceed slowly. C. A more complicated excursion of the equilibrium over Δt still produces a rebound immediately after $\hat{D}'$ exceeds diversity. From Sepkoski (1984).

diversification". Each period of repetition should be carefully documented within each taxonomic group (planktonic foraminifera, coccolithophores) where it has been identified. Documentation should include species' proportional abundance through these times, rates of change for lineages within groups, biogeographic variations in diversification, among-group comparisons, and separation and documentation of these data for morphotypical groups (*e.g.* keeled vs. non-keeled planktonic foraminifera). Other plankton records (diatoms, silicoflagellates, radiolaria, etc.) should be inspected to ascertain the degree to which repeated diversification in these groups occurs.

With this documentation, the following questions should be addressed: What is the degree of synchroneity among various groups' diversification ? Do the benthic biota, including foraminifera and ostracodes, show repeated diversification and to what degree is it synchronous with the plankton ? Do particular morphotypes within each group display synchroneity ? Can any of the morphotypes be identified with particular biologic processes known in living representatives ? Is there a correlation between this repetition and measurable environmental factors ? How do variations in within-group diversification patterns correlate with known or inferred biologic and environmental factors ? What is the relationship of repeated diversification to post-extinction and general radiations (see above) ?

With answers to these questions, we may learn whether intrinsic factors or environmental influence on diversification and selection operating on different organisms are important in their evolution, and whether such factors operate across taxonomic groups.

Nearly Monospecific Acme-Layers

Oceanic sediment layers consisting of dense, nearly monospecific or monogeneric calcareous phytoplankton ("blooms") are known from several time intervals. Examples include *Watznaueria* in the uppermost Jurassic, *Thoracosphaera* and *Braarudosphaera* in the lowest Danian, *Braarudosphaera* in the Oligocene, and *Gephyrocapsa* in the upper Quaternary. These oceanic acme events have so far only been observed for the calcareous phytoplankton. Their occasional association with period boundaries has led to their interpretation as opportunists that attained dominance during productivity collapses (oligotaxic periods of Fischer and Arthur, 1977). Alternatively they could also be caused by preservational processes. The interpretation of these nearly monospecific layers, however, remains enigmatic, partly because of the scarcity of continuously recovered and suitably preserved sediment sequences.

EXTINCTION EVENTS

Dramatic Decline in Abundance

Dramatic declines in the content of calcareous plankton in oceanic sediments are observed in the middle Aptian and at the K/T boundary. The declines have likely been caused by decreased supply (*i.e.* carbonate fixation in the photic zone), rather than by increased dissolution, because all well-preserved fossils are from sediment samples with relatively low carbonate contents. The few known oceanic high-carbonate sediments from these intervals are dominated by micrite which appears to be of diagenetic origin. Was the dearth of oceanic biogenic carbonate fixation related to trapping of carbonates (and nutrients) on shelves (*e.g.* climate, sea-level, etc.) or was it an independent biological phenomenon ? What were the effects of such supply changes on the cycling of carbon in the ocean ?

Extinction Rates, Major and Minor Extinction Events

Extinction has gone on at all times in the geologic past. However, very little is understood about what causes extinction and how continuous or episodic extinction has been. Are rates of extinction relatively constant over millions of years, or are they highly variable ? Do species extinctions occur more or less independently of one another, or do they tend to be clumped in time (Raup, 1986) ? Are extinction events distinct from background extinction, or is there a continuous spectrum of phenomena from background extinction through minor extinction events to major mass extinctions ? And, are mass extinctions simply scaled-up versions of smaller, clumped extinctions ? Investigations of these questions require detailed global range charts with fine temporal resolution and comparative studies of extinction patterns in different ecological groups, water masses, and ocean basins.

Cretaceous/Tertiary Boundary

The substantial amount of detailed research stimulated by the bolide impact hypothesis has served to provoke further questions that can only be answered by yet more research in a variety of disciplines. The most important of these questions from a paleobiological point of view are (a) the extent to which the end-Cretaceous mass extinction event was gradual or sudden in geological terms, (b) the degree to which extinction was selective towards certain groups, and (c) the character of the post-extinction biotic recovery. For all these subjects, the marine microfossil record is better than any other because of the abundance and wide distribution of fossil material and the fine chronological resolution. The biotic patterns established by further detailed research in the oceanic realm, from the tropics to the poles and from inner shelf to open sea, will have an important bearing on which extinction scenario is ultimately the best supported, whether extraterrestrial impact or processes intrinsic to this planet, or even a combination of extraterrestrial and terrestrial processes such as bolide impact triggering volcanicity (Alvarez, 1986; Jaeger, 1986; Officer *et al.*, 1987). At the present time, the extent of oceanic coverage of the K/T boundary is very limited. Many more data are required from both hemispheres, and especially the unexplored polar regions, because both the volcanic and the impact-expelled dust cloud scenarios have testable implications for different latitudes. High-resolution study of boundary samples substantially undisturbed by core recovery is required for the detailed comparison of iridium profiles with the patterns of successional change in microorganisms, and to evaluate the role of bioturbation or redeposition in causing iridium dispersion through the sediment. Shocked quartz should be searched for and its pattern of regional distribution and size variation determined. Detailed carbon and oxygen isotope profiles should be extended for some meters both above and below the K/T boundary and possible correlations sought with biotic change, in order to put the boundary events into a better understood temporal context. A transect of cores from shallow to deep marine facies, as for example in the eastern North Atlantic, could prove very illuminating in testing certain predictions. This includes the expectation that an oceanic impact should have given rise to immense tsunamis that may have stripped extensive areas of shelf and upper slope and redeposited the sediment on the deep ocean floor (other predictions are of course possible).

Jurassic/Cretaceous Boundary

A diversity decrease in the marine plankton near this boundary has been documented in the Atlantic and Tethyan Oceans (Roth, 1986). No record whatsoever has so far been recovered in the Pacific.

Aptian

The late Aptian is characterized by a decline in diversity of planktonic foraminifera (Fig. 4) and increased taxonomic turnover of calcareous nannofossils (Thierstein, 1983) and calcareous benthics. This interval is also characterized by the first true black shales ("Selli Event") at the beginning of the

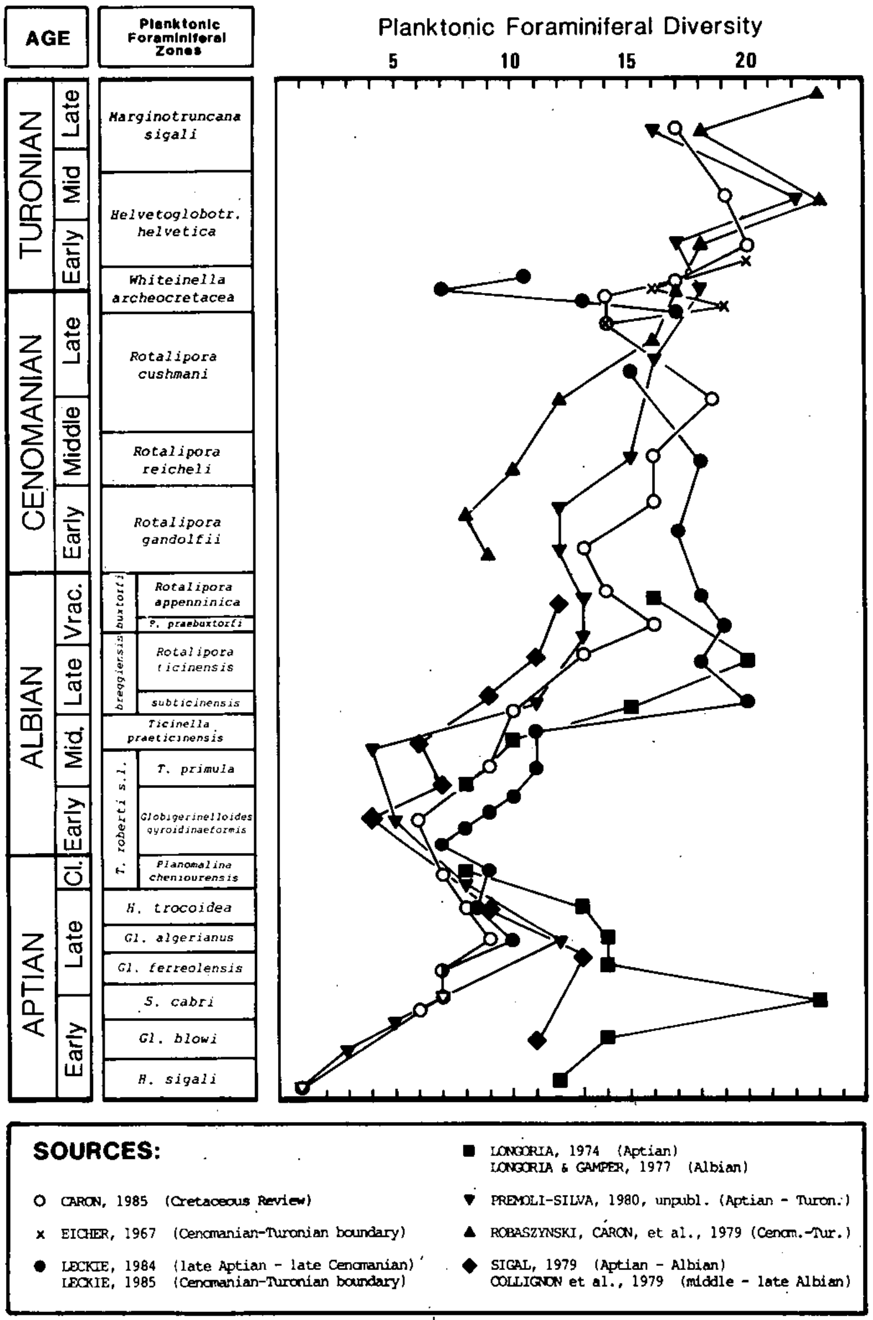

Figure 4. Simple planktonic foraminiferal diversity through the mid-Cretaceous. These curves record the first major radiations of planktonic foraminifera. Specialized morphotypes repeatedly appeared during Aptian, late Albian and early to mid-Turonian times. Declines in planktonic foraminiferal diversity (species number) during latest Aptian-early Albian and latest Cenomanian-earliest Turonian times are associated with the loss of such morphotypes. The latter intervals are also coincident with the widespread accumulation of organic carbon. Sources selected on the basis of preservation of material from sections studied and completeness of assemblage documentation (*i.e.*, all species accounted for and not simply the biostratigraphically useful forms). From Leckie (in press).

long interval of Cretaceous black shale sedimentation. The causal relationship between these events (and perhaps also the beginning of the long middle Cretaceous magnetic quiet zone) needs to be investigated.

Cenomanian/Turonian Boundary Event

The Cenomanian/Turonian boundary is globally marked by the presence of laminated, organic carbon-rich black shales that either lack diverse benthic foraminiferal assemblages (Fig. 5) or contain only a depauperate agglutinate fauna; planktonic foraminifera and radiolarians are, however, abundant. A marked positive $\delta^{13}C$ spike marks the boundary (Scholle and Arthur, 1980). The question arises as to what extent the plankton or benthos were affected by this apparent global anoxia. Proposed anoxia models need to be tested by a study of benthic foraminifers in different paleobathymetric and latitudinal settings.

Late Paleocene Benthic Event

The Paleocene is poorly known; biogenic marine sections are rare to date. Yet the Paleocene was characterized by the largest changes of $\delta^{13}C$ in carbonates of any epoch in the Cenozoic, and the late Paleocene by the heaviest values of $\delta^{13}C$ (Shackleton, 1986). These $\delta^{13}C$ changes have been interpreted (Shackleton *et al.*, 1986) in terms of variability in productivity in the ocean surface waters, where the isotopically heavy values represent high productivity and the drastic lightening during latest Paleocene times reflects a "crash" in marine productivity. Foraminiferal evolution has in the past been associated mainly with temperature variability (*e.g.* Berggren, 1969). These late Paleocene productivity changes suggested by the $\delta^{13}C$ record occurred at a time of significant sea floor spreading rate changes (Berggren *et al.*, 1985) and are associated with the most profound taxonomic turnover among the benthic foraminifera known during late Cretaceous to Paleogene times, including the K/T boundary (Tjalsma and Lohmann, 1982). Recent evidence (Corfield, 1987) suggests two peaks of taxonomic turnover in planktonic foraminifera related to the productivity changes in the Paleocene (Fig. 6). Were there any cause and effect relationships ? Did productivity changes trigger this evolutionary turnover in the plankton as well as benthos ? Clearly there is a need to locate, drill, and analyse continuous deep-sea sections that include good Paleocene sections in order to address these problems.

Eocene/Oligocene Boundary

Three stratigraphically and geochemically distinct microtektite layers of presumed impact origin have been found in Upper Eocene sediments (Keller, 1986). However, only one of these microtektite layers appears causally related to planktonic foraminiferal extinctions (four species), whereas the other two coincide with major abundance decreases in both planktonic foraminifera and nannoplankton. One of the layers has anomalously high iridium content and coincides with radiolarian extinctions (five species ; Saunders *et al.*, 1984). The Eocene/Oligocene boundary is characterized by the extinction of the planktonic foraminiferal groups of *Hantkenina* and *Globorotalia cerroazulensis*, which occurred several 100 000 years after deposition of the microtektite layers and which appear unrelated to the impact events (Pomerol and Premoli Silva, 1986). These data show that impact events are not necessarily directly related to extinctions but may alter population dynamics.

At some sites, one microtektite horizon is coincident with a major change in the relative abundance and significant morphometric changes of planktonic foraminifera species. It is not clear what role the physical event that produced the tektite horizons played in constraining subsequent populations. Analyses of coeval populations from sites more distant from those rich in tektites will provide tests of the alternative hypotheses of reversible (ecophenotypic) versus genetic responses (MacLeod *et al.*, 1987). These significant and unresolved phenomena require much more detailed study in well-preserved ODP cores and detailed quantitative studies on all major plankton groups as well as benthics.

Mid-Miocene to Pliocene

Unusual numbers of extinctions and high faunal turnover occur in marine plankton (planktonic foraminifera and diatoms) at the end of the Middle Miocene and earliest Late Miocene. This faunal change is usually associated with major carbonate dissolution in the deep sea. Therefore, at present the details of this extinction/dissolution event are unknown. More dramatic extinctions of planktonic foraminifera appear to have occurred at the Miocene-Pliocene boundary (Wei and Kennett, 1986), but much better quantitative documentation of these changes in foraminifera and other microfossils is required.

Selectivity of Extinctions

There are a number of fundamental but open questions about patterns of taxonomic selectivity at extinction events that can be answered with detailed range data derived from oceanic drilling. Flessa *et al.* (1986) list the following unassessed factors relating to how victim and survivor species differ :

- Abundance (are rare species more susceptible to extinction ?)
- Geographic range (are endemic species more susceptible ?)
- Tropical vs. extratropical setting (are tropical species more susceptible ?)
- Productivity (are species in low-productivity habitats more susceptible ?)
- Body size (are species of large-bodied individuals more susceptible ?)
- Clade richness (are species-poor clades more susceptible ?)

Documentation of correlations between extinction and any of these factors will have important implications for evolutionary paleobiology.

OTHER ENVIRONMENTAL EFFECTS

Mid-Cretaceous Anoxia

Planktonic foraminifera increase in average size and total numbers beginning in the middle Aptian and lasting to the base of the Albian (Fig. 4). Through the early Albian, planktonic foraminifera are sparse and limited to few species. During the early and middle Albian, oxygen levels appear to have decreased in the water column as a whole because of an excess of organic matter, which is an important contributor of the characteristic black shales. Restoration of more normal conditions at the end of the anoxic interval may have produced a new radiation of planktonic foraminifera, and possibly radiolaria, in the mid-Albian, with forms developing that show little phylogenetic relationship with faunas found below the event (Arthur and Premoli Silva, 1982 ; Leckie, 1984 ; Delamette *et al.*, 1986). By the end of the Albian, planktonic foraminifera were largely diversified. Deep-water benthic foraminifera diversified taxonomically and ecologically between the Barremian and the Santonian into a succession of bathymetrically differentiated assemblages covering neritic to bathyal environments. New forms (including the first buliminids, a low-oxygen preferring group) appeared in the latest Albian, when planktonic foraminifera also diversified (Sliter, 1986). The question thus arises : Were the mid-Cretaceous taxonomic diversification of plankton and benthos and the observed ecological specialization of deep-water benthic foraminifera related to the development of global anoxia ? Strategically placed, continuously cored depth transects may provide answers to this question.

Inception of Psychrosphere : Cause of Evolutionary Acceleration in the Eocene ?

A number of biotic changes occurred in the Eocene that may be related to the development of cold bottom waters. Early Paleogene cosmopolitan benthic foraminifera and ostracodes were replaced in the Middle Eocene (mainly during the P11 to P13 interval) by new taxa showing increased provinciality. New planktonic foraminifera (globigerinids) developed and the spinose acarininids and morozovellids became extinct. Deep-sea ostracodes changed and shallow-water larger foraminifera (nummulitids and alveolinids) became extinct. The causes of these events are unknown but seem related to the restructuring of the global ocean circulation, where the cold, deep water reservoir (psychrosphere) developed (Benson *et al.*, 1984). Complete Eocene sections must be identified and drilled if the interrelationships between polar cooling and evolution of oceanic microbiota are to be analyzed.

Stasis in the Oligocene, despite Antarctic Ice Accumulation and Global Sea-Level Drop ?

The Oligocene is a period of rather gradual taxonomic change in benthic and planktonic biota in spite of possible major environmental changes indicated by the biggest oxygen isotopic shift and the most dramatic sea-level drop known in the Cenozoic (Haq *et al.*, 1987). Among nannofossils, species gradually disappeared and, as few new species appeared, the flora became progressively less diverse. Planktonic foraminifera were less diverse, and globular, chambered forms dominated among the larger species. The important globorotalids showed the first (although still non-keeled) species. The most notable change in foraminifera in the Oligocene was among the smaller species where pseudohastigerinids were gradually replaced by a strong dominance of heterohelicids, which in turn decreased

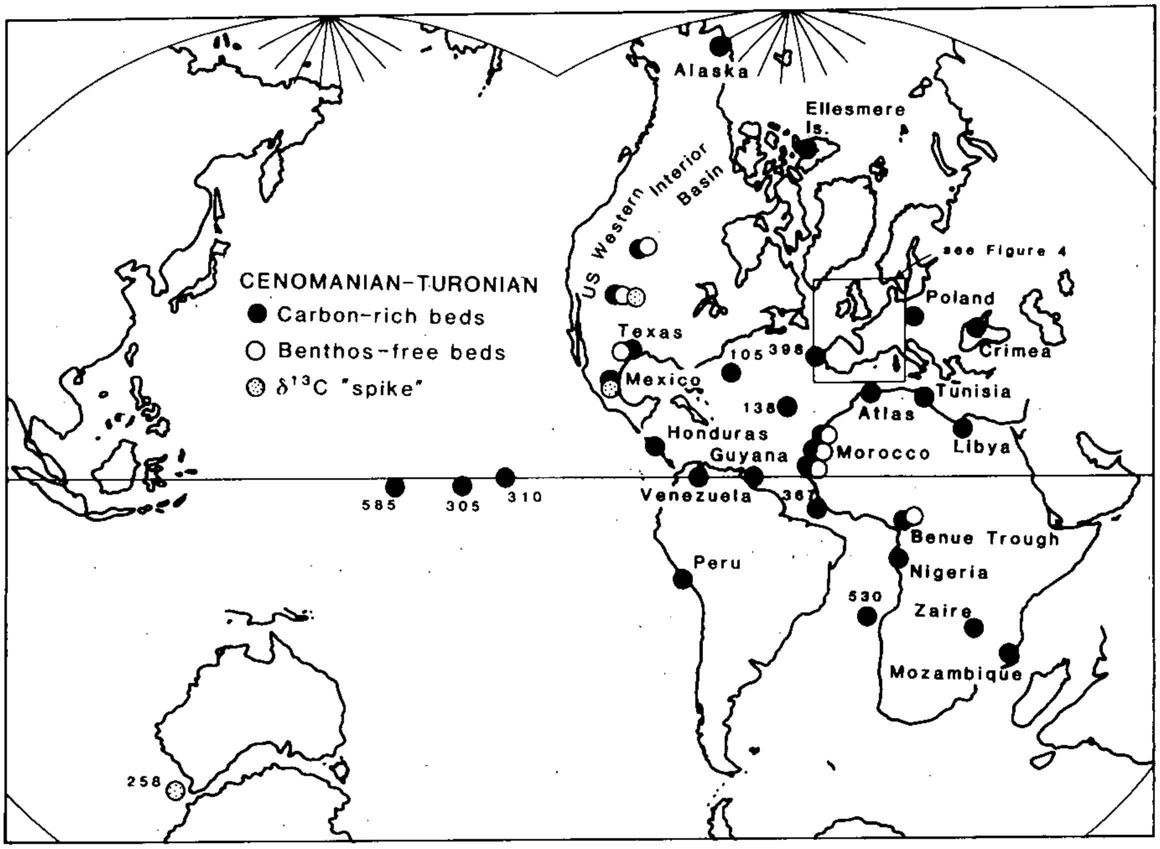

Figure 5. Map of the world at 90 Mybp showing locations of Cenomanian-Turonian sections (other than those in Europe) and the lithologic, paleontologic and carbon isotopic peculiarities of the boundary layers. Deep Sea Drilling Project Sites are designated by number. From Schlanger *et al.* (1987).

again dramatically before the end of the Oligocene (Cifelli, 1969 ; Stainforth *et al.*, 1975).

Late Neogene Climate Cycles

Is cyclic climatic change driving oceanic plankton evolution ? Late Neogene oceanic microfossils are suitable for testing the two contrasting hypotheses of taxonomic evolution : the *Red Queen hypothesis* and the *Stationary model* (see above). The evidence from planktonic foraminifera is currently equivocal and similar studies of other groups, particularly of siliceous organisms from the Arctic and Antarctic, are necessary to reach a consensus about macro-evolutionary patterns in oceanic microfossils.

Bolide Impacts

Bolide impact craters on continents are known and can be dated, such as the Duolun crater in China, which has a diameter of about 170 km and a radiometric age of about 135 Ma (Wu Si-Ben, 1987). Can contemporaneous layers be identified by geochemical or evolutionary signals in oceanic sequences covering the Jurassic-Cretaceous boundary in the region ? Are evolutionary signals, especially extinctions, present at times of this and other known impact events ?

Other attractive objectives are possible impact sites in ocean basins that could be drilled (*e.g.* Jansa and Pe-Piper, 1987). A number of submarine topographic features have been identified that may be impact craters of bolides. Geophysical surveying methods should be employed to evaluate the likelihood that these features are impact sites. The recovery of impact melts by drilling into such structures may be of great value in evaluating the geochemical composition and, by comparison with known K/T-boundary clays, the terrestrial fractionation processes of bolide- and melt-derived trace elements.

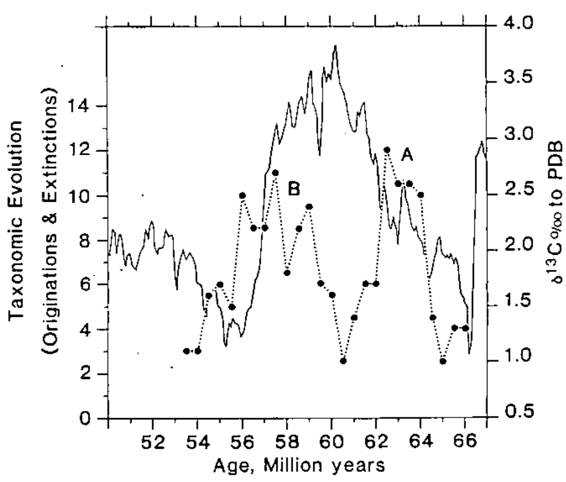

Figure 6. Taxonomic turnover per 0.5 million year interval (dots) and carbon isotopic changes of planktonic foraminifera (solid line) suggesting peaks in evolutionary turnover just prior and after a major global plankton productivity change in the late Paleocene. From Corfield (1987).

OTHER BIOLOGICAL PHENOMENA

Problems dealing with the inferred biology of fossilizable organisms are excluded from most traditional paleobiologic questions in ocean drilling. Such studies bear importantly on all previously discussed items in this paper, but require more study on characters *per se* within a phylogenetic context and environmental setting. Such studies include, but are not limited to, function (including physiology), life history phenomena (reproduction, mortality), ecologic requirements. Much of the thorough documentation suggested for other objectives in this chapter will provide the basis for this kind of inference in paleobiology.

Appearance of Functional Groups

Functional analysis of certain fossil organisms has provided valuable insight into a wide variety of evolutionary questions. This kind of approach to the fossil record of the oceans may similarly provide powerful input to a wide range of topics considered previously in this chapter, as well as for their own intrinsic merit.

Among the oceanic plankton and benthos are groups whose modern biology is sufficiently well known to provide an adequate basis for paleobiologic inference. For example, planktonic foraminiferal reproduction in some groups is associated with depth segregation and morphologic change, and their feeding habits are related to the possession of spines (Bé, 1980 ; Hemleben and Spindler, 1983). With careful analyses of ontogenetic morphologic change and spinosity, the evolutionary history of reproductive and feeding strategies in planktonic foraminifera may be deciphered. Other techniques may be applied to these problems, as well ; in particular stable isotope analysis of individual specimens or parts of specimens. Once such interpretations are possible, comparisons with other evolutionary and environmental data, and between different functional groups within taxonomic units, can be made.

Some questions that might be addressed are : How do reproductive strategies differ among groups, with time, with various evolutionary events (extinctions/radiations), and do these differences bear on the historical developments of the group ? Do photosynthesizing organisms vary in their evolutionary record from non-photosynthesizing organisms ? How do inferred symbiont-bearing species within groups (*i.e.* shallow benthic and planktonic foraminifera) differ from those inferred not to have harbored symbionts ? Do groups that can be inferred to have segregated with depth within their life cycles differ from those that did not (*i.e.* planktonic foraminifera and radiolaria) ? How do taxa that are inferred to have been at particular levels in the trophic structure (Spindler *et al.*, 1984) vary from those at other levels (*i.e.* carnivorous vs. herbivorous planktonic foraminifera ; or infaunal vs. epifaunal benthic microfossils) ? The answers to these and other such paleobiologic questions will provide bases for estimating the role of selection on and adaptations in oceanic biota.

Evolutionary Patterns in Different Ecosystems

Ecological relationships among co-occurring fossils provide a means for assessing a variety of evolutionary questions and for understanding the historical development of oceanic ecosystems. As stated above, the ecological roles of organisms must commonly be inferred from other data. Such data will likewise be obtained by careful documentation of morphologic, abundance, and biogeographic observations and measurements provided by other analytical techniques such as stable isotopic analyses.

Important questions here are sought not only from paleobiology but from modern ecology as well, which is simply the result of a long history obtainable only from the fossil record. Many of these questions seem best answered through comparative studies between very different ecosystems (in a loose sense). How do nutrient fluctuations through time affect evolutionary diversification and extinction in pelagic and shallow carbonate settings (Hallock and Schlager, 1986) ? Can trophic relationships be determined by comparison of plankton and benthos residing in eutrophic versus oligotrophic oceanic regions ? What are the histories of these relationships through time and how do they differ ? Are changes in the ecologic structure of one ecosystem mirrored or reflected in changes in other ecosystems (*i.e.* pelagic vs. deep-sea benthic vs. reefal biotopes) ? Does ecologic structure of distinct ecosystems seem to be linked in a direct fashion, for example through nutrient supply (*i.e.* oceanic plankton as a trophic resource for reef organisms ; or pelagic for deep benthos) ? Does evolution proceed differently in high and low latitudinal water masses ?

Answers to these kinds of questions can be developed into hypotheses relating to the major biologic directions outlined in this paper, which are amenable to further testing.

Molecular Markers

The recent discovery of biomarkers that are specific to certain phytoplankton taxa, such as long-chain alkenones, as well as the frequencies of amino-acids, hold the potential for identification of phylogenetic relationships of morphologically distinct groups or for verification of speciation events in the absence of preserved skeletons (Brassell *et al.*, 1986 ; King and Hare, 1972). Deep-freezing of core material for such analyses should continue to be part of any future core curation.

Diachroneity of Biotic Appearances

Some first or last appearances of planktonic taxa are known to be time-transgressive, such as seen in certain late Cenozoic planktonic foraminifera (Fig. 7) and radiolaria (Johnson and Nigrini, 1985). Such diachroneity is common in the Mesozoic and Cenozoic. The evolutionary change from cosmopolitanism to bipolar or even unipolar distributions, such as is observed in *Coccolithus pelagicus*, may give new insights into certain mechanisms responsible for extinctions. Such studies are only possible in well-dated and well-correlated high-resolution sedimentary records, so rare in the existing core inventories. High-resolution correlation will permit identification of geographic source areas where allopatric or sympatric speciation events may occur (Emiliani, 1982).

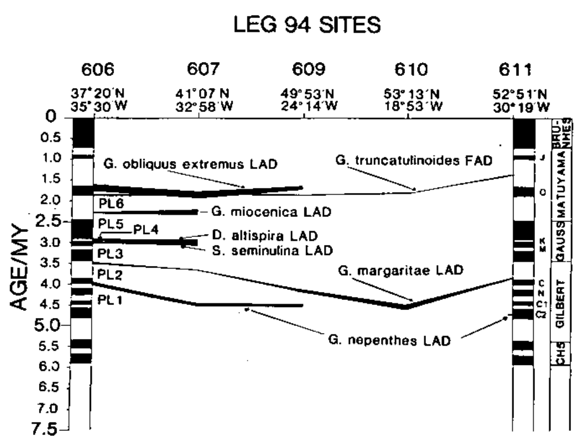

Figure 7. First (FAD) and last (LAD) appearance datums of species used in the sub-tropical zonation (Berggren, 1973, 1977). Sites 606-610 run S-N ; Site 611 lies under colder water masses than Site 610. Thickness of bar = error between sample spacings. Note diachroneity of *G. truncatulinoides, G. margaritae and G. nepenthes* datums. From Weaver and Clement (1986).

Fossil and Living Bacteria

Bacterial studies of the sedimentary record have important implications for paleo-microbial geochemical studies and for understanding bacterial post-depositional, diagenetic influences on the fossil record. Data on both the living and fossil bacterial populations and their "activity" are required.

Within the last few years, two mineral products of bacterial origin have been found in marine sediments: (1) chains of ultra-fine grained magnetite particles (magnetofossils) produced by the magnetotactic bacteria (Petersen and Von Dobeneck, 1986; Stolz *et al.*, 1986; Fig. 8) and (2) casts of manganese/iron-precipitating bacteria (Cowen and Bruland, 1985; Cowen *et al.*, 1986). Magnetofossil preservation implies the existence of an oxygen gradient at the mud/water interface and an influence on paleomagnetic data. The manganese/iron casts have been interpreted as an indication of the activity of nearby hydrothermal vent plumes. Valuable insight into paleo-geochemical conditions, such as hydrothermal venting and oceanic redox conditions, may be obtained by the examination of the sedimentary record for the presence and chemistry of such fossil remnants of bacteria. The potential of similar paleo-bacterial studies can not be overstated, as over 15 minerals are now known to be precipitated directly by bacteria, and many of these have distinctive compositions and/or unique crystal habits (Lowenstam and Weiner, 1983). Non-living bacterial cell walls and extra-cellular polymers are also likely important in the formation of late-stage diagenetic phosphate and sulfide minerals (Beveridge *et al.*, 1983).

Although living bacteria are abundant and diverse in the top few meters of the oceanic sediments, their impact on ecology and the process of diagenesis is poorly understood. Little is known also concerning the activity of bacteria as a function of depth within deep-sea sediments. Bacterial activity has been suspected in salt domes and in oil fields, and may be related to the presence of diagenetic magnetites (*e.g.* McCabe *et al.*, 1987), but to our knowledge, living bacteria have never been systematically searched for in freshly recovered deep-sea sediment. Knowledge of bacterial activity at depth and as a function of sediment type could be important for the interpretation of chemical mobility of many elements, such as iron, lead, copper, and manganese which are scavenged by microorganisms. Samples recovered with the HPC technique would be best for these studies, as they have a minimum of disturbance from the drilling process and are not bathed in contaminated drilling mud.

STRATEGIES, TECHNIQUES

Chronology

The chronostratigraphic analysis of deep-sea sediments is one of the basic requirements for any analysis of the evolution and extinction of oceanic biota. Various forms of magnetic and

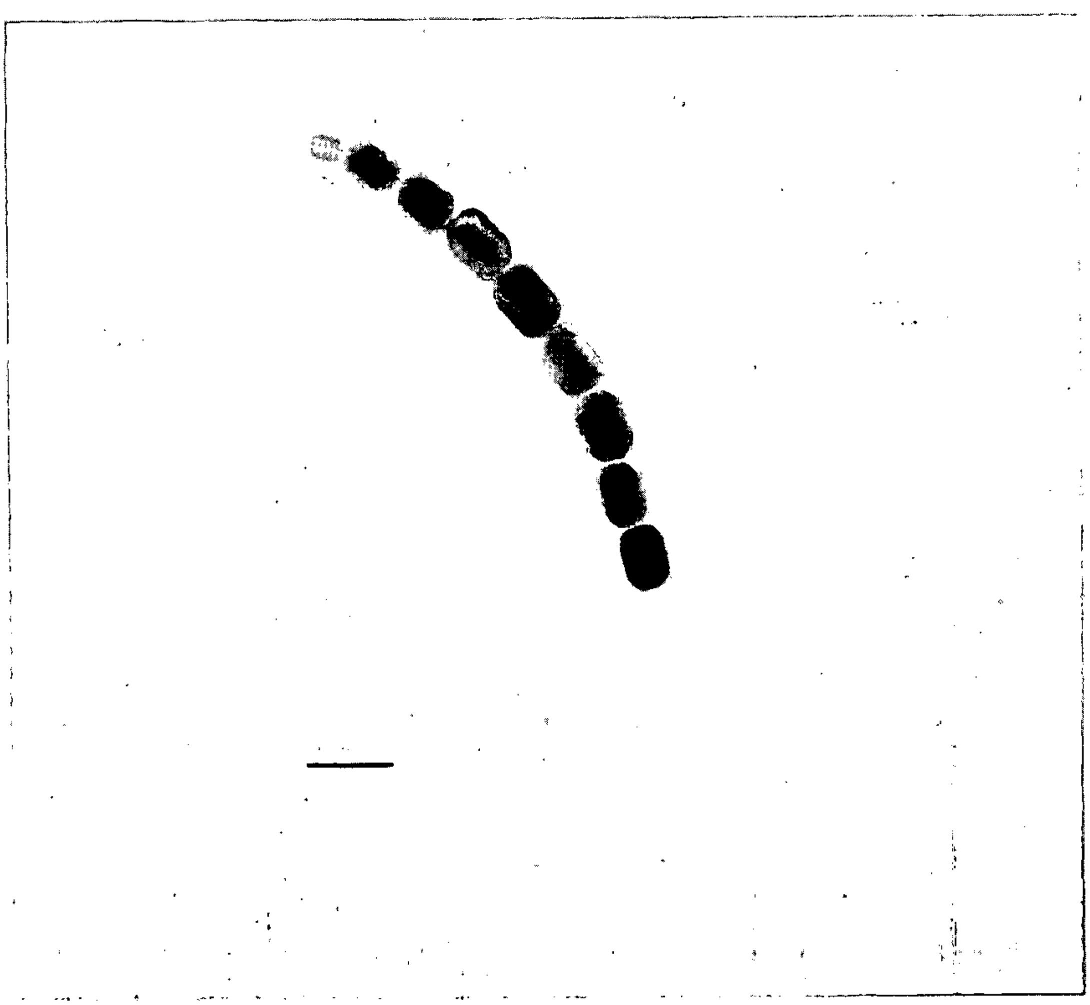

Figure 8. Bacterial magnetofossil from marine sediments of the Santa Barbara Basin, southern California. Scale bar is 0.1 micrometer.

stable isotope stratigraphy, as well as radiometric dating, provide both relative and absolute time scales for studying long continuous sedimentary sequences. However, the analyses of the evolutionary models discussed earlier in this paper imply that it will be necessary to exploit and refine these chronologic techniques relative to what has been done previously.

Reliability of Biostratigraphic Events

The biostratigraphy of oceanic microfossils is known to considerable detail (Bolli *et al.*, 1985), but there is still room for substantial improvements. These can be achieved primarily through analysis of the reliability of the species events used in the existing zonal schemes. Assessments of the reliability depend on understanding the complex interaction of species in ecological assemblages through time. A simple approach to this problem is quantification of the abundances of marker species which reflect their productivity flux. Species showing sharp rises (First Appearance Datums) or sharp declines (Last Appearance Datums) in abundance at the end-points of their stratigraphic ranges are most suitable as biostratigraphic indicators, particularly if such markers show consistently high abundances after their appearance or before their extinction. Morphometric data are also proving to be useful. Recent advances are taking biostratigraphy from the discrete mode (based on the ranges of qualitatively described taxa) to the continuous mode (based on the quantitative assessment of morphological change).

Magnetostratigraphy

Geomagnetic polarity transitions are the only frequent, globally synchronous geophysical phenomena, and it is widely recognized that high-precision magnetostratigraphy is of paramount importance to the resolution of various problems in the correlation of oceanic sediments. Paleomagnetists concerned with the Ocean Drilling Program have identified three periods of geologic time for which further improvements in the correlation of biostratigraphy to the magnetic polarity time scale are badly needed (Verosub *et al.*, 1986) : (1) the Bathonian, Callovian and Oxfordian stages of the Jurassic, (2) the Valanginian to Hauterivian stages of the Early Cretaceous, and (3) the Middle and Late Miocene.

In addition, it has been shown that the magnetic field has small characteristic oscillations in both direction and intensity (secular variations) that have proven useful for stratigraphic correlation in Pleistocene sediments, and similar variations have been identified in strata as far back as early Mesozoic. Although secular variations may be produced by a random process in the Earth's core (Constable, 1987) and therefore might not possess characteristic frequencies, they might still be of use for measuring relative time around short duration biologic events, such as the Cretaceous/Tertiary boundary extinctions. Further work is needed to determine whether geomagnetic secular variation has been constant over the last 100 million years, whether or not there are characteristic periodicities, and which types of oceanic sediments are capable of preserving them. These questions could be answered best with continuous (HPC) coring in areas with high deposition rates that preserve Milankovitch rhythms.

Whole-core paleomagnetic measurements must be conducted routinely, and as rapidly as possible after recovery, on all core material obtained with the HPC. Although the existing superconducting magnetometer system is adequate for this purpose, it is overly dependent on supplies of liquid helium. Development of a more flexible superconducting system, free of the liquid helium requirement, should be strongly encouraged by the Ocean Drilling Program. The use of recently-discovered high-temperature superconducting materials, coupled with improvements in the technology of closed-cycle cryocoolers, makes this possibility realistic.

Isotope Stratigraphy

Due to the geologically short mixing time in the world oceans, variation in the isotopic ratios of oxygen, carbon, sulfur, and strontium are often globally synchronous. In addition to providing information concerning climatic changes, a refined knowledge of these variations may also be of use for high-resolution stratigraphy and would provide further calibration of the Tertiary $^{87}Sr/^{86}Sr$ curve of DePaolo and Ingram (1985) and Elderfield (1986).

Chemostratigraphy

Carbonate and organic carbon cyclicity have been identified in numerous statigraphic intervals. Because they may be climatically induced, their potential should be further studied in continuously cored, paleomagnetically dated sequences. Rare events, such as bolide impacts or giant volcanic explosions, may leave distinct elemental traces in the deep-sea record which may be used for very accurate correlations. For instance, iridium-rich horizons have been identified and studied not only at the K/T boundary but also at other distinct levels (*i.e.* Cenomanian, Upper Eocene, Middle Miocene, Pliocene), with sometimes contradictory results. Particular attention should be paid in future study not only to the abundance of Ir but also to the identification of the iridium carrier, which might prove of crucial importance in assessing its terrestrial or extraterrestrial origin. Detailed trace elemental and isotopic analyses (*e.g.* lead) of deep-sea sediment cores should therefore be encouraged.

Radiometric Calibration

Past efforts to calibrate radiometrically the biostratigraphic and magnetostratigraphic time scales in oceanic sediments have largely focused on dating the contacts of the basement volcanics with the overlying sediment. Another approach, however, is to search systematically for volcanic ash units that may be datable using $^{39}Ar/^{40}Ar$ techniques, in all of the core material returned ; this would be easily done with a magnetic susceptibility unit of the sort mentioned above.

Automation of Paleontological Data Collection

The goals of testing the evolutionary models outlined previously in this chapter will require routine and intensive micropaleontological analyses of all major planktonic groups. High-density measurements of species diversity and within-taxon morphologic variability should be conducted on all well-dated continuous core intervals, but this is clearly beyond the present limits of the micropaleontology community. Some form of automation for routine species identification appears to be necessary. Prototypes of computer-controlled systems for identifying and sorting foraminifera have been developed (Johnson, 1980), and the prognosis for their improvement and use as a routine, ship-board tool appears to be good.

Some of the major bottlenecks inhibiting progress in these fields are a result of the imprecision and bulk of the information generated. To improve the quality of newly-acquired information, and to be in a position to use effectively the much greater volume of data and cores that will be accumulated through the 1990's, we need now to experiment with the application of *artificial intelligence technology* to this problem.

A fundamental weakness of paleontological data results from the inconsistency and imprecision with which names are applied to fossils. In ten to twenty years this problem may be solved by automated recognition of fossils through image analysis. As a step toward this end, we can now use computer programs that help the paleontologist to identify fossils more consistently by providing shape templates and annotated illustrations.

Additionally, to help stratigraphers make more precise and reliable age determinations, a computer program could provide a readily modifiable, comprehensive biostratigraphic and magnetostratigraphic framework covering all microfossil groups and all biogeographic regions. This total, integrated stratigraphic framework would be anchored to the concrete reality of the reference collections of DSDP microfossils being assembled at eight repositories strategically located around the world.

It would be appropriate for the JOIDES Information Handling Panel now to begin coordinating the development of the various components of the "expert system" and its necessary data bases, so that they can be tested during the current phase of ODP drilling.

Quantity of Recovered Material

There is wide agreement among scientists involved in the ODP that the amount of recovered sediments is often too limited to perform all the (usually destructive) experiments that are needed in evolutionary and geochemical studies. The result of this limitation has often been that fine-scale correlations of events recorded in samples from exactly the same stratigraphic levels have not been possible. Possible answers to this problem include using a larger, *e.g.* 10 cm-diameter, HPC corer which would provide a 44% increase in the volume of material recovered, or by multiple coring at each site to overcome drilling disturbances and stratigraphic gaps. There should be a strong policy that samples be shared, with processing done in a sequence that is as little destructive as possible, both on and off shore.

Transects

Paleobiological analyses most often require knowledge of the spatial as well as the temporal changes present within a stratigraphic section. Outcrop-based studies on land, for example, have the advantage over the present drilling program that they permit regional gradients in species diversity and phenotypic evolution to be measured directly. An intensive drilling program, however, could overcome this by collecting continuous cores over a grid or transect pattern across environmentally interesting areas (such as across a passive margin according to a latitudinal gradient including the Arctic Ocean). A drilling program of this sort would make it possible to test some of the models discussed earlier.

Recovery of Older, Well-Preserved Sections, Obtainable by Hydraulic Piston Coring in Submarine Outcrops

The methods to be employed in analyses of evolutionary processes are quantitative. They require well-preserved, completely recovered sequences that can be dated with bio-, magneto- and chemostratigraphic techniques and, presumably, high-resolution chronology using orbital (Milankovitch) frequencies. Such records are obtainable with hydraulic piston coring techniques, which have recently become employed very successfully to recover Neogene sections in the later legs of DSDP and particularly during ODP drilling. No such records, however, are yet available to study the major evolutionary events prior to the Miocene. We urge that a systematic survey of existing seismic reflection profiles be undertaken to identify suitable pre-Miocene sections in or near submarine outcrops, where older, unconsolidated and well-preserved sediment sequences of a few hundred meters thickness each, covering various stratigraphic intervals, can be obtained efficiently.

Availability of Existing Sediments and Data Bases

When planning future stratigraphic work and checking on the adequacy or otherwise of material already on hand from earlier DSDP holes, it would be extremely valuable to have a constantly updated data base that would tell us for any given interval :

- the number of sites available and their recoveries and lithologies ;
- the abundance and preservation of each of the microfossil groups at those sites ;
- the distribution of these sites in the various ocean basins ;
- the availability of magnetostatigraphic and other chronologic data ; and
- the availability of isotopic data.

We emphasize that some of the existing data are wrong or incomplete, and the data group should be supported to improve it. Some of this information can certainly be obtained from the DSDP data bases set up by the DSDP Data Handling Group. We urge that these activities be continued and expanded if necessary to include magnetostratigraphic information as well as all results from subsequent post-cruise research. As the number of sites continues to grow and the individuals connected with the Project decreases, we suggest that such a structured data base should be set up and continually updated to assist future planning.

Finally there is the problem of determining which drilled cores are available for study of any particular microfossil group or lithologic type from a particular region and/or a particular span of geologic time. The user also needs to know the degree of completeness of the desired age-span at each of its occurrences. The solution is a full stratigraphic (including lithostratigraphic) data base of DSDP and ODP cores, capable of being updated at the end of each leg. This would require that the drilling ship be equipped with PCs compatible to those commonly utilized by scientists so they could take with them the parts of the data base needed for their shore-based work.

Hard/Soft Drilling Technology

To achieve many of the goals described in this document, it is imperative to have good recovery of geologically older material. Given the occurrence of chert and limestone beds in otherwise soft sediments, this will require new technology to drill in material of varying resistance. The development of this technology is considered an important goal for ODP.

SUPPORT FOR RELEVANT BIOLOGIC STUDIES

Evolutionary and extinction studies, as proposed in this chapter, must be based on thorough, relevant biologic information (see above). Information of this nature is not always of interest to biologists and/or funding sources. We therefore strongly urge that biologic studies, particularly of shelled organisms, that address the issues discussed in this chapter be supported by appropriate funding agencies. We further urge that this sentiment be passed by ODP to the national funding agencies supporting these activities. Funding or other support of these activities are not appropriate to ODP, but ODP must acknowledge their importance to the success of some of its goals.

RELATIONSHIP TO OTHER SCIENTIFIC PROGRAMS

The International Geosphere-Biosphere Program (IGBP) includes a great number of physical scientists who realize that most of the pressing environmental issues that now face us transcend the bounds of traditional scientific disciplines and that, as global problems, they require more than national efforts for their solution. From the initial thrust on global change and the implications of environmental change for people and the future, the concept of the IGBP was developed. The main focus of IGBP is "to describe and understand the interactive physical, chemical, and biological processes that regulate the Earth's unique environment for life, the changes that are occurring in this system, and the manner in which they are influenced by human actions" (NRC, 1986). To recognize the effects of human interference with the global environmental systems requires precise knowledge of the evolution and past (natural) variability of these environments and their interaction with and effects on the biosphere. That record is uniquely preserved in sedimentary rocks and, for a much shorter interval, in ice caps. We consider it, therefore, essential to evaluate this natural background of environmental and biotic variability, which can most efficiently and successfully be done by studying the deep-sea depositional record.

Two other IGCP projects, Rare Events in Earth History (IGCP 199) and Bioevents (IGCP 216), would benefit greatly from global biogeographic studies in the deep sea.

Over the past few decades, a great deal of effort has been put into tying the mammalian fossil record to the magnetic polarity time scale. By using this common time scale, events in the oceanic record can be precisely correlated with events on land. We encourage efforts to increase intellectual ties with groups working on continental sequences.

The Global Ocean Flux Study (GOFS), which is geared up for full implementation in 1989, will make a comprehensive study of materials entering and falling through the water column of the world ocean during the same decade as ODP will be investigating the fate of those materials after they reach the water/sediment interface. Both of these programs will be carried out in the framework of water-mass distributions and biogeographic regions, and each would benefit from an effective liaison between them.

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5**

TECHNOLOGICAL WHITE PAPERS

Present and Future Technology for Scientific Ocean Drilling

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ABSTRACT

This chapter begins with a brief summary of the origins of scientific ocean drilling, the technology which was available at the outset and that which had to be developed to make the Deep Sea Drilling Project (DSDP) a viable operation. After 15 years of operation with the *Glomar Challenger*, this technology was smoothly transferred to the new Ocean Drilling Program (ODP) for use with the *JOIDES Resolution*.

The problems of drilling in difficult formations are then described, some of which have dogged the quest to penetrate and sample the ocean floor since the early days of DSDP: fractured basalts, loose and broken rocks, unconsolidated sands, chert, sloughing clays and shales. New scientific objectives emphasised by the 1981 COSOD I meeting - drilling zero-age crust on mid-oceanic ridges, hydrothermal systems, drilling and coring deeper - add to the technological challenge which faces ODP. ODP's progress in meeting this challenge is outlined.

The advantages and disadvantages of radically new approaches to scientific ocean drilling are discussed. These include the use of a full-diameter oil-field riser system, a slimline riser, mining style drilling and a dual pipe system with a sea floor mud reservoir.

It is concluded that major engineering development must be undertaken if ODP is to be able to meet its scientific objectives. Modifications to the existing ODP drilling system cannot provide the answers to the major drilling challenges being faced; major new drilling systems need to be acquired. However, at present a disproportionately small percentage of the total budget of ODP is devoted to developing the technology, only 3.3%. Substantial increases in the money and staff available for engineering development need to be made.

INTRODUCTION

After a few abortive starts, most conspicuous of which was the Mohole Project, scientific ocean drilling began in 1968 when the dynamically-positioned drilling vessel *Glomar Challenger* started work at sea. Over the next fifteen years *Glomar Challenger* drilled 1092 holes at 624 sites worldwide, recovering in the process 96 km of core. Initially, the Deep Sea Drilling Project (DSDP) was funded solely by the United States National Science Foundation. But so successful was it and such was the international interest that from 1975 onwards five other nations joined in the funding of what was known as the International Phase of Ocean Drilling (IPOD).

This major scientific programme was initiated on technology pioneered largely by the oil industry - rotary drilling, automatic pipe racking, wireline coring, dynamic positioning. Other essential technological ingredients, needed for the precise navigation of the drill ship, came from defence and from oceanography itself. *Glomar Challenger* was one of the first civilian users of the Transit Satellite system developed by the US Navy. Oceanography provided the deep-ocean acoustic beacons needed as fixed references for the dynamic positioning.

The technological mix outlined above was to form the basis of *Glomar Challenger* drilling. But it soon became apparent that it was not enough and that further technological development would be needed. The two most important developments during the course of DSDP were (a) Hole Re-entry and (b) Hydraulic Piston Coring. For the first few years of DSDP, the maximum penetration that it was possible to achieve in an ocean floor borehole was determined by the life of the drill bit. Hole re-entry, first achieved on Christmas Day 1970, is now used routinely in scientific ocean drilling in water depths of up to 6000 m. Although it was soon realised that rotary drilling destroyed most of the fine structure of unconsolidated sediments, it was not until Leg 64 in 1978, ten years after the start of DSDP, that hydraulic piston coring (HPC) was first successfully employed. Subsequent development of the HPC technique led to the Advanced Piston Corer which is routinely used in the Ocean Drilling Program today.

At the end of 1983 *Glomar Challenger*'s fifteen year career of ocean drilling came to an end. In January 1985, ODP commenced operations at sea with the drilling vessel *JOIDES Resolution*. Constructed in 1978 as a dynamically-positioned drill ship capable of riser drilling in water depths of up to 2 km, *JOIDES Resolution* is a considerably larger and more powerful vessel than *Glomar Challenger*. Modified for ODP, she can drill in riserless mode in water depths of 8.2 km and support a drill string up to 9.1 km long.

Although the start of the new drilling programme involved the setting up of a new facility at Texas A & M University and the closing down of one at the University of California, San Diego, the technology and expertise of DSDP were not lost. On the contrary, the changeover has been remarkably smooth, with key technical personnel moving from DSDP to ODP. With engineering development more clearly identified as a part of the programme, ODP is now poised to meet the challenges which the scientific objectives entail.

THE TECHNOLOGICAL CHALLENGE

Drilling in Difficult Formations

A very wide range of lithologies and drilling conditions are encountered in scientific ocean drilling. This variety will not diminish as new scientific objectives are added to those which already exist. Where massive or thick-bedded formations, ranging from limestone and cemented sandstones to basalt, have been drilled, good results have often been obtained. But where formations are disaggregated, fractured or thin-bedded, serious difficulties frequently arise. It is convenient to divide the difficult formations into five categories: fractured basalts, loose and broken rocks, unconsolidated sands, chert, sloughing clays and shales.

The problems faced when drilling these difficult formations are broadly as follows :

(a) Unstable hole conditions develop during the drilling operation so that further drilling and coring become impossible. Although it may still be possible to log the hole down to the depth at which instability occurs, failure to reach the target depth seriously impairs the scientific value of the hole.

(b) The rate of core recovery in certain lithologies is unsatisfactory. Some compensation for low recovery rates can be obtained by downhole logging.

(c) On completion of the drilling and coring operation, the longer term stability of the borehole is inadequate to allow logging or other downhole experiments.

Out of 97 holes drilled on the first eleven legs of ODP, 25 suffered from serious stability problems which impaired the coring and logging operations (Table 1). The percentage failure rate is considerably worse than these figures imply because a substantial proportion of the holes attempted were planned only for shallow penetration with the hydraulic piston corer. Failure to reach target depth and to log the hole drilled inevitably increases with the depth of penetration planned.

Fractured Basalts

Older basement rocks buried beneath a blanket of sediment have been sampled by scientific ocean drilling for many years, sometimes with considerable success. Secondary alteration minerals, filling the fractures and pores, facilitate the penetration of the drill. In contrast, the very young, fractured basalts found at oceanic spreading centres beneath negligible sediment cover present the most difficult drilling conditions encountered in the ocean. The solidification and rapid cooling of magma in contact with seawater on the ocean floor leads to intensely fractured pillow and sheet flows with hard glassy margins. The physical properties of this material are similar to those of broken bottles.

Attempts to drill and core young fractured basalt have so far been disappointing. Engineering development carried out by ODP to do this is described in a later section. Major problems remain to be solved :

(1) Core recovery is low because the highly fractured rock tends to disintegrate during the drilling process, producing irregularly shaped fragments which jam the inner core barrel or the core catcher.

(2) Although the initial rate of penetration after spudding in on bare rock is quite high, unstable conditions usually develop after a few metres of penetration due to rock fragments falling from the walls of the hole. This material, accumulating in the annulus around the drill collars and above the bit, results in torquing and sticking of the drill string.

(3) The hard and sharp-edged basalt fragments are extremely abrasive so that the tungsten carbide roller-cone core bits used wear out in only 5-10 hours.

It has already been mentioned that older, altered basalts are much easier to drill. But with depth into basement the degree of alteration and secondary mineralization decreases, so that fractures in the rock can still present a problem.

Exceptionally stable hole conditions were encountered in Hole 504B for more than a kilometre into basement. On ODP Leg 111, however, drilling conditions deteriorated markedly at about 1400 m below the sea floor with torquing and sticking of the drill string and difficulty in hole cleaning. This was accompanied by anomalously high rates of penetration and a low rate of core recovery. Downhole logging measurements subsequently indicated overgauge hole and "breakouts" of the hole wall 180° apart. This shattering of the hole wall probably reflects the tectonic stresses in the region of the hole and may also have been triggered by the thermal stress imposed by drilling fluid (seawater) more than 100°C lower in temperature than the rock at the bottom of the hole. Fracturing due to thermal stress could explain many of the drilling and core recovery phenomena encountered on Leg 111.

Table 1. Problem holes on the first eleven (drilling) legs of ODP. Coring had to be suspended at these holes, either because of stuck pipe or because of the fear that pipe would stick if coring proceeded further. Inevitably, any downhole logging programme was abandoned.

Leg Number	Site/hole	Depth BSF (metres)
101	626B	?
101	626D	1033
101	634A	562
101	635A	20
101	635B	156
103	637A	285
103	638B	384
103	638C	547
103	639A	80
103	639B	127
103	639C	100
103	639D	293
103	639E	234
106	648B	33.4
107	651A	141
107	654A	352
108	659B	202
108	661A	296
109	648B	50.5
109	670A	92
110	671B	91
110	672A	324
110	675A	36
112	682A	429
112	683A	419
112	683B	488
112	685A	431
112	688B	365
112	688E	779

Loose and Broken Rocks

Loose and broken rocks are encountered in a variety of environments and lithologies. Ice-rafted material, talus deposits, nodular chert and shallow-water reef limestones are among the formations which are capable of producing loose boulders and fragments which can disrupt the drilling and coring process. In severe cases, unstable hole and stuck-pipe problems similar to those of fractured basalt may result. More commonly the harder rocks will roll around under the core bit, destroying the softer host rock before it can be cut into core.

Loose and broken rocks are often quite local in their occurrence and can be avoided by careful selection of drill sites.

Unconsolidated Sands

Uncemented sand or gravel deposits of clastic, biologic or volcanic origin are included in this category. Sand deposits are extremely difficult both to penetrate and recover in the core barrel with existing ODP equipment. In the petroleum industry, however, sands are frequently encountered and are routinely handled by means of circulating mud systems and casing.

Sand flowing up the annulus of an ODP borehole tends to fall back down the hole when the pump circulation is stopped for a wireline core retrieval trip. A sand/seawater slurry can then flow back through the bit, into and around the inner core barrel, sometimes covering it completely. The core barrel may either be jammed in the pipe or impossible to engage. If it is not possible to re-establish circulation and clear the sand when this happens, pipe has to be pulled and the hole abandoned. Even when sand does not interfere with the core retrieval, it can pack around the drill collars and jam the drill string. When the annulus is thus blocked, re-establishing circulation can be impeded by the low fracture strength of the formation which limits the pressures which can be used.

Where mud is circulated, sand strata can be stabilized by means of additives that "plaster" the wall of the hole and reduce fluid loss into the sand. Thin beds of sand can be stabilized in this way in ODP, but there is little hope of stabilizing massive or numerous beds with the intermittent mud "pills" available in riserless drilling. Increased circulation rates to clear sand from the hole can be counter-productive because they accelerate erosion of the unconsolidated beds.

Sand is not easily penetrated by the hydraulic piston corer so that cores seldom exceed 1-2 m in length. Better success is achieved with conventional rotary and XCB coring, but sedimentary structures tend to be destroyed in the process. Retention of the core in the barrel during its wireline trip up to the drillship is a further challenge, since sand grains can cause leakage in the ball check valve at the top of the barrel and sand is easily washed from the core catcher at the bottom of the core barrel. Improved varieties of core catcher can improve the degree to which the core is retained.

Chert

The occurrence of chert in deep sea sediments has been a source of frustation to scientific ocean drilling since the early days of DSDP. It tends to be found in Eocene and older sediments and has proved particularly toublesome in the Northwest Pacific. Thick layers of chert can be difficult to penetrate, even with the toughest tungsten carbide roller-cone bits presently in use. Interbedded layers of hard and soft material, such as chert and chalk, are extremely difficult to recover. Fragments of chert tend to jam the entrance to the core barrel, effectively becoming part of the bit and preventing softer material from entering.

Poor recovery of alternating hard and soft layers led to the development of the extended core barrel (XCB) system. In soft sediment, the spring-loaded core barrel extends through the orifice of the roller-cone bit, allowing its narrow kerf to cut the core undisturbed by the bit jet hydraulics and the action of the roller-cones. The XCB system has now been used for a few years and in some cases has proved more effective than conventional (RCB) coring. It continues to be developed.

Sloughing Clays and Shales

The vast majority of scientific drill holes in the ocean floor are completely uncased. It is not surprising therefore that problems of hole stability or difficulty in cleaning a hole are often encountered which limit the achievement of coring and logging objectives. With clay, claystone and shale formations hole deterioration may be due to mechanical or chemical causes. Determining the precise nature of a hole instability problem is made more difficult in ODP drilling by the absence of a return circulation to the drill ship, so that there are no cuttings or mud properties available for study.

In the first place, clays and other soft sediments can be eroded by the fluid flow. "Washouts" form in the softer layers, leading to a reduction in the annular velocity and the accumulation of cuttings at these locations. When circulation is stopped, as happens during core retrieval, cuttings tend to fall back down the hole. Eventually a hole cleaning operation becomes essential.

Using seawater as the drilling fluid implies that the hole is always underbalanced relative to the pressures in the rock. When the strength of a formation is insufficient to support this pressure differential, to which overburden pressure, lateral tectonic stress and other forms of geopressure can contribute, parts of the wall of the hole may fall off into the hole, leaving behind an enlarged hole. Alternatively plastic deformation can lead to a reduction in hole diameter. In the latter case repeated reaming of the hole may be necessary to keep it open for continued operations. Plastic deformation problems are encountered in ODP drill holes at much shallower penetrations than they become a problem in the petroleum industry.

Chemical instability of clay-bearing sediments can occur when the sedimentary pore water is more saline than the fluid filling the hole. In that situation cations can be lost from and water enter the clay mineral structure, so that the clay swells and softens. Montmorillonite and smectite are the clay minerals principally responsible for this process. The problem can occur either when the sedimentary pore water is more saline than the circulating seawater in the hole or when a freshwater/bentonite mud slug is used to clean the hole. Alternative seawater-based muds are being evaluated and may prove to be the best for filling the hole for logging.

Engineering Development for Drilling and Coring Young Fractured Rocks

Developing the technology to drill young, fresh volcanic rock in areas with little or no sediment cover has been a major engineering objective of the Ocean Drilling Program since its inception. Although the axes of the mid-oceanic ridges are the prime focus for this development effort, similar drilling conditions can be encountered in back-arc basins and on seamounts. Two ODP drilling legs have been dedicated to the task to date, Leg 106 at the end of 1985 and Leg 109 in 1986, both concentrating their efforts at a single hole (Hole 648B) on the Mid-Atlantic Ridge. A third attempt at hard rock drilling is planned for the Southwest Indian Ridge on Leg 118 towards the end of 1987.

Prior to Leg 106 attempts to spud at crustal sites with minimal sediment cover had repeatedly resulted in the loss of all or part of the unsupported bottom hole assembly (BHA). It was therefore necessary to acquire new items of equipment and to develop new techniques in order to be able to tackle the problem. These were are follows :

1. Hard Rock Guide Base (HRB)

This box-shaped structure 17 ft (5.2 m) square by 11 ft (3.4 m) tall, weighing about 18 tonnes in air, is designed to sit on the sea floor to provide lateral support for the BHA and to constrain the drill bit while it spuds in on the bare rock. The base incorporates a cone 16 ft (4.9 m) in diameter and 6 ft (1.8 m) deep. The HRB is designed to land on slopes of up to 20° covered with boulders of up to 3 ft (0.9 m) diameter. An acoustic beacon telemeters the angle of tilt back to the ship. Once on the bottom, bags in the base of the HRB can be filled with 2000 ft^3 (57 m^3) of cement to provide additional mass.

Experience on Leg 106 indicates that, provided the weather conditions are reasonable, assembly and deployment of the HRB can be successfully achieved in about 2 days.

2. Positive Displacement Drilling and Coring Motors

In routine drilling and coring operations on the *JOIDES Resolution* the drill string is driven from the top. In order to minimise the lateral forces on the BHA when spudding in, downhole motors, driven by seawater pumped down the pipe, were employed on Legs 106 and 109 for rotating the bit. Two types were used :

5•••

(a) Positive Displacement Drilling Motors (PDM). With a drill bit attached, only the lowermost portion of the motor and the bit rotate. It is also possible to attach an RCB or XCB core barrel to the PDM in order to take an single core. However wireline retrieval through the PDM is not possible.

(b) Positive Displacement Coring Motor (PDCM). This differs from the PDM in allowing wireline retrieval of core barrels. A much greater length of motor rotates (approximately 12 m) to transmit torque to the bit. Nevertheless it allows the upper part of a hole to be cored when the bulk of the BHA is unsupported. The greater length of the rotating part makes this motor more likely to stall than the PDM in sticky hole conditions.

3. Subsea TV System

A vibration-isolated frame carrying TV camera and lights has been developed which can be run up and down the outside of the drill string by means of a coaxial cable. This allows real-time observation of the sea floor near the bottom of the pipe to water depths of 6000 m. The system was found to be very effective on Legs 106 and 109, being used to survey in detail the HRB site and to monitor re-entries.

4. Drill Bits and Core Bits

Conventional roller-cone drilling and coring bits were used on both Legs 106 and 109. Due to the abrasive drilling conditions on Leg 106 core bit life was limited to 5-6 hours. New designs of bit, incorporating improved wear protection features, were used on Leg 109 and resulted in improved bit life.

The rate of penetration achieved on Leg 106 was found to be inversely related to the diameter of the drilling and coring bits used :

18 1/2" Drill Bits - 0.3 m/hr.
14 3/4" Drill Bits - 0.4 m/hr.
9 7/8" Core Bits - 1.5-2.0 m/hr.

5. Cementing

Much time on Legs 106 and 109 was spent drilling rubble out of the hole and freeing stuck pipe. Severe stalling of both the downhole motors and the top drive was experienced. Cement plugs were pumped at the end of selected bit runs in an effort to enhance hole stability. They prevented the hole from caving when the bits were pulled and possibly cemented together some of the fractures in the hole wall.

Lessons Learned from Legs 106 and 109

Deployment of the HRB proceeded as planned and the guide base provided the lateral support and bit confinement necessary for the hole to be spudded in. Only minor modifications are necessary for future HRB deployment. The problem of spudding in on bare rock may be regarded as solved.

The original drilling plan for Hole 648B was to drill an 18 1/2" hole and set 16" casing to 30 m depth, followed by coring with 14 1/2" and then 10 1/2" bits. A second string of 11 3/4" casing was to be set, according to drilling conditions, to 90-150 m depth. In the event this plan proved impossible to carry out. After much expenditure of drill bits, the 16" casing was eventually set to only 8 m below the sea floor. On Leg 109, 10 3/4" flush-jointed casing was set to 28 m depth. After 55 operational days on both legs the total depth achieved was only 50 m (Fig. 1). The major problem encountered was hole instability. The lack of progress was due to having to re-drill rubble that filled the hole between each bit run. Over 165 m of rubble was drilled and cored. Furthermore, the larger the diameter of the hole being drilled, the greater was the instability. With hindsight it can be seen that it was a mistake to attempt to drill such large diameter holes in fractured, broken material. However, starting off at a small diameter limits the ability to case the hole with the drilling equipment presently available to ODP.

In addition to their role at Hole 648B, several unsupported bare rock holes were attempted with the positive displacement drilling and coring motors. In soft formations, such as hydrothermal vent deposits and serpentinized peridotite, this proved feasible and valuable cores were acquired using the PDCM (Site 649, Hole 670A). However, the percentage core recovery was in general very low. With the PDM, unsupported spud in proved possible even on fractured basalt, a 4.5 m hole being drilled at Hole 648A. Again recovery was very low.

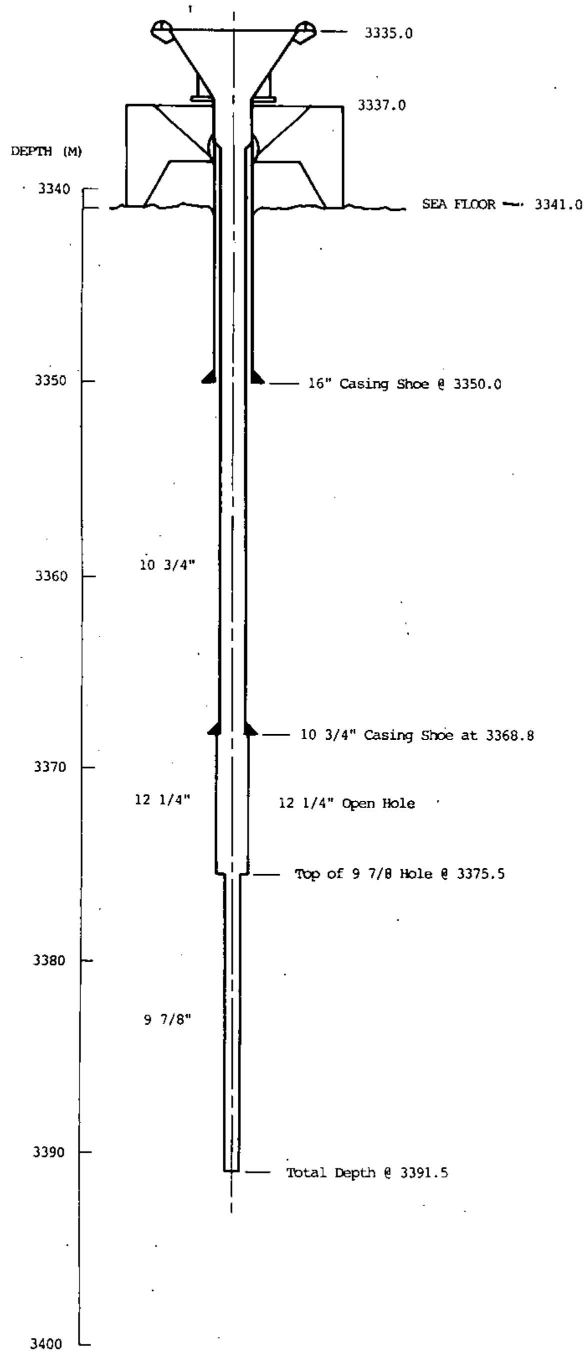

Figure 1. Configuration of Hole 648B after two legs of drilling.

The most important application of the capability to make unsupported spud-ins with the PDM or the PDCM may not be for scientific sampling but for test drilling the sea floor prior to the deployment of the HRB. This should help ensure that when the HRB is deployed, always likely to be a rare event in scientific ocean drilling, it is in the right place.

Finally the considerable difficulties experienced on Legs 106 and 109 and the low rate of core recovery place in question the whole style of drilling, essentially that developed for the petroleum industry, for tackling fractured basement rocks. A slim hole, high rotation speed, low weight-on-bit, approach has been used with success on land in the mining industry. Application of this mining style of drilling to the ocean is currently under study at ODP.

Problems in High Temperature Drilling

The High Temperature Environment of the Ocean Floor

There is strong scientific interest in drilling into very young oceanic crust where high temperatures exist. There are essentially three distinct thermal environments where such drilling might be carried out :

(1) Sediment-free mid-oceanic ridge axis where water is being vigorously discharged at temperatures of up to 400°C, for example the East Pacific Rise at 13°N. Theoretical calculations suggest that the temperature within an upwelling zone does not increase significantly with depth until very close to a magma chamber, where it may rise several hundred degrees in a few metres. Zones where water is drawn down are much more extensive in area and temperatures here probably remain below 100°C to depths of 1500 m. However, large lateral variations in sub-sea floor temperature and hydrothermal flow rates may exist.

(2) Mid-oceanic ridge where the axis is buried beneath thick sediments, for example the northern Juan de Fuca Ridge. The relatively impermeable sediment cover impedes the discharge and recharge of seawater into the basement hydrothermal system. Zones of upwelling within the basement are likely to be broader than in sediment-free areas of the axis, with the basement generally reaching higher and more uniform temperatures. The permeability of the basement rock may be lower than in sediment-free areas due to alteration of the rock and cementation of the fractures and voids.

(3) Off-axis areas of young oceanic crust where pervasive sediment cover inhibits significant hydrothermal convection and a conductive regime prevails. Hole 504B in 6 My old crust generated at the Costa Rica Rift is an example. Maximum bottom hole temperatures of about 150°C were experienced on Leg 111. Deepening this hole by a kilometre would increase the bottom hole temperature to well over 200°C.

Engineering Development for High Temperature Drilling

It is clear from the above that ODP needs in the near future to be able to drill, core and make downhole measurements at temperatures of up to 400°C. In the longer term a much higher temperature capability may be required if drilling close to or into magma chambers is considered a worthwhile scientific objective. The considerable worldwide activity in geothermal drilling on land in recent years will be particularly beneficial to ODP's efforts to develop a high temperature capability, for much development work has already been carried out and 400°C is regarded as "start-of-the-art" in land-based geothermal drilling. In order to transfer this technology for use on the ocean floor it is necessary to consider the effect of high temperature on all the individual components used in the drilling process and on the system as a whole :

Drill string. There should be no loss of strength of the drill pipe and bottom hole assembly at temperatures up to 400°C since this is below the temperature used in the heat treatment of high strength steels. However, high temperatures can lead to over-tightening of tool joints so that they cannot be broken at the rig floor. Special tool joint compounds have been developed for high temperatures.

Bits. Conventional sealed-journal-bearing rock bits are not suitable for high temperature drilling due to premature failure of the seals and bearings. However, unsealed roller bearing bits with tungsten carbide inserts are believed to be viable up to 400°C. Furthermore, specially developed sealed-journal-bearing rock bits have been used successfully in the Salton Sea geothermal hole up to 343°C. Diamond bits are also thought to be viable to 400°C.

Downhole Motors. Positive displacement motors of the type used on Legs 106 and 109 deteriorate at temperatures approaching 200°C, well short of the 400°C target. An all-metal construction turbodrill exists which is rated to 320°C. Although developed for directional drilling, it is thought that it could be adapted for straight hole drilling and wireline coring.

Drilling Fluids and Cement. The muds presently used in ODP for hole cleaning are not suitable for the high temperatures proposed. However, suitable muds have been used in geothermal drilling and will have to be provided for high temperature holes in ODP. Similarly, high temperature cements will be needed for the installation of casing.

Downhole Corrosion. Hydrothermal fluids, which are acidic and rich in H_2S, could have an extremely corrosive effect on the steel of the drill pipe and bottom hole assembly. High temperatures would accelerate corrosive attack. Careful monitoring of the drill string will be required with borehole fluid samples taken when corrosion is suspected.

Core Liners. Core liner material suitable for temperatures up to 219°C, known as Ultem 1000, has already been used in ODP. On Leg 111, these liners were used to take the first core after each re-entry, being exposed to maximum temperatures of 150°C. Conventional butyrate liner, which is satisfactory to about 140°C, was used for subsequent cores as the hole was then cooled sufficiently by the circulating seawater.

For temperatures above 219°C, the use of metal or fibreglass liners or no liners at all should be considered.

Hole Cooling. The fluid circulated in the drill hole can be used to maintain the borehole temperature below the limits set for particular tools and instrumentation. Considerable experience of the flow rates required, the extent to which the temperature can be lowered and the rate at which it can recover when the flow is stopped is available in the geothermal drilling community. ODP has its own experience from operations at Hole 504B.

Analysis of Steam Flash Conditions. The danger of drilling into an active ocean floor hydrothermal system without some form of blow-out prevention was pointed out in the 1981 COSOD I Report. A reduction of pressure within the pipe could be caused by pulling a core barrel or other wireline tool. Superheated water might then rise up the pipe, flash to steam and lead to a dangerous flow of steam onto the rig floor.

A number of computer simulations of ridge crest hydrothermal drilling have now been performed and in some cases, particularly where the water depth is shallower than usual, do predict steam venting at the rig floor. Further work needs to be done to explore the validity of these models and to establish what actions need to be taken on the ship to prevent a dangerous situation occurring.

Alternative Methods to Allow ODP to Drill/Core Deeper

The 1981 COSOD I Report concluded that scientific ocean drilling would continue in the riserless mode throughout the nineteen eighties. However, it was also thought in 1981 that the development of riser drilling would continue to progress into deeper water in the ensuing decade and that the riserless technique might be capable of reaching maximum penetrations of the ocean floor of as much as 3000 m. With hindsight it is now possible to see that both the latter predictions were optimistic.

The maximum water depth in which riser drilling has been successfully carried out by the oil industry remains at the 6952 ft (2119 m) achieved in 1984 off the US East Coast. Water depth maxima for 1985 and 1986 were substantially less and future progress in this area seems more difficult to predict now than it was six years ago.

The maximum penetration of the ocean floor by riserless drilling remains at the 1740 m achieved at Hole 398D on Leg 47 of DSDP in 1976. Prior to the return to Hole 504B on Leg 111 of ODP, it was thought by many that this record would be broken. In the event it was possible to deepen that hole by only 212 m, to a total depth of 1562 m ; core recovery of the sheeted dykes drilled amounted to only 13%. Furthermore, there was evidence that the style of riserless drilling with seawater circulation employed might have been approaching its limits at this hole.

Problems of hole stability, difficulties in reaching the target depth, difficulties in cleaning the hole and low core recovery have led to considerable thought being given to what alternative styles of drilling need to be adopted to allow ODP to meet its scientific objectives. The following alternatives have been considered or are still under consideration.

1. Modifications to ODP's Present Drilling System

Difficulties in cleaning the hole might be improved by increasing the annular velocity of the seawater circulation back to the sea floor. This could be achieved in three different ways :

(a) Drilling a smaller hole. A study already carried out by ODP shows that decreasing the size of the bit and drill collars is not a useful option. Bit life and the strength of the drill collars would be unacceptably reduced.

(b) Increasing the size of the drilling assembly. If this were done while retaining the same bit size, the annular volume would be reduced. Annular velocity would increase, but so would the pressure loss in the circulating fluids. Larger cuttings might be more difficult to clear and the tendency for the drill string to stick might increase. Nevertheless, the concept needs further examination.

(c) Adding a Jet-Sub to the drilling assembly. Circulation through the drill bit is limited by the need to avoid erosion of the core and drilling an enlarged hole. The circulation pumps on the ship are capable of much greater flow rates. Increased circulation might be beneficial if a proportion could be diverted into the annulus before it reached the bit (Fig. 2). Hole cleaning might then be improved without increased erosion of the core.

The latter concept is worth pursuing further and has the added attraction of not being expensive, either in money or drill ship time.

2. Using an 18 1/2" Oilfield Riser System

Use of a full marine riser as employed in the offshore oil industry would allow drilling to be carried out with mud circulation back to the drill ship and full well control to be maintained. There is no doubt that this would solve many of the technical problems currently encountered in riserless drilling. However, the disadvantages of such a system for scientific ocean drilling are manifold and rule it out of serious consideration :

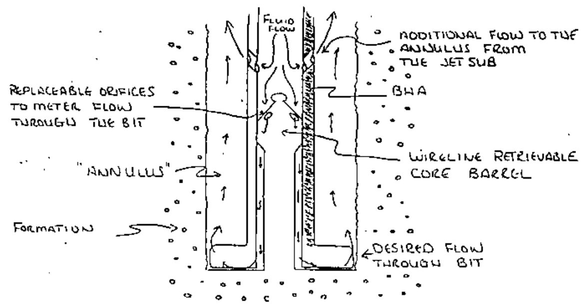

Figure 2. Jet-Sub concept for improving hole cleaning.

(a) An oilfield riser system is very expensive. (Cost comparisons of different drilling systems are given in the next section). The cost of converting the *JOIDES Resolution*, back to a 6000 ft (1828 m) (the maximum for this ship) riser drilling capability alone was estimated in April 1987 to be in excess of $ 11 M (Steere, 1987). Furthermore, this water depth capability is insufficient for most of the ODP targets which might benefit from riser drilling.

(b) Considerable time would be spent simply in deploying and retrieving the riser. Deploying a riser in 10 000 ft (3048 m) water depth would take several days, assuming ideal weather conditions. In the course of a year only 3 or 4 riser holes could be drilled in the place of 30 or 40 riserless holes drilled at present, though the amount of rock penetrated would be comparable.

(c) Full riser drilling in deep water is technically risky. As the water depth increases, the resonant period of the riser-tensioner system moves into the range where most of the wave energy lies. The dynamical problems get worse when the riser is disconnected, which could happen because of storms, failure of the dynamic positioning or during its construction or dismantling. Failure of the riser in these circumstances can occur.

(d) Even with a deep water riser capability, the problem of the fracture strength of the rock remains. Before a riser and a mud circulation could be used in 10 000 ft (3048 m) water depth, a sedimentary hole would have to be cased to 4500 ft (1372 m) below the sea floor to prevent loss of circulation.

3. Slimline Riser System

Deepwater marine risers used in the oil industry are typically about a metre in diameter because of the buoyancy material attached. Without distributed buoyancy, the force required at the top to hold the riser in tension becomes excessive. However, smaller diameter pipe, intermediate in size between the drill pipe used in ODP and the diameter of oilfield riser pipes, can be supported entirely from the top in oceanic depths and serve as a riser. The feasibility of suspending 9 5/8" pipe to oceanic depths has already been demonstrated in manganese nodule mining trials (Zinkgraf, 1987). A preliminary analysis of the operation of a 15 000 ft (4572 m) riser of this diameter has been carried out and indicates that it would be feasible. However, it would require an installed tensioning capacity on the drill ship of around 700 tonnes, which may be excessive for the *JOIDES Resolution* (Sparks, 1987).

Another disadvantage of this type of riser is the limitation it sets on the diameter of the downhole tools. The problem of the fracture strength of the rock is the same as with a full riser system.

4. Mining Drilling System

Drilling and coring in the mining industry has developed in a very different way from that of the oil industry. The style of the latter has been to drill large diameter holes at low r.p.m. with heavy weight on the bit - what is essentially a grinding process. By contrast, the mining industry has developed small diameter, high speed drilling with less weight on the bit, which is more akin to machining. Moreover, the ability of this system to recover core in hard rock is impressive. On land mining type drilling has been used to depths of 15 000 ft (4572 m) (Johnson, 1987).

Characteristic features of the mining system are : use of the drillpipe as casing, the very small annulus employed, the exclusive use of drag bits, continuous coring capability. Three different sizes of drill rod are available, each in turn fitting inside the other, for drilling holes of up to 5.25" diameter. Thus two casing strings under 5.25" diameter are available. Typical dimensions of the drill rod, hole and core sizes are :

System	Hole Size	Core Size	Rod O.D.	Minimum Rod I.D.
CHD76	2.98"	1.713"	2.754"	2.165"
CHD101	3.99"	2.5"	3.701"	3.091"
CHD134	5.25"	3.344"	5.0"	4.125"

The applicability of the mining approach to ocean drilling is currently being studied at ODP. Among the areas which need investigation are the ability to hang-off drill string as casing in a subsea hanger when it is stuck in the hole, ability to detect the weight on the bit, and the combination of the mining system with the slimline riser.

5. Dual Pipe Subsea Mud System

The most original approach to drilling with mud has been advocated by Schuh (1987). In this system a reservoir of mud on the sea floor keeps the annulus between the drill pipe and the hole wall filled with mud (Fig. 3). Conventional drill pipe is used from the surface down to some point above the sea floor when dual wall pipe is needed. A special flow controller is required at the junction of the two kinds of pipe, which would divert the flow down the annulus of the dual wall pipe when coring, yet allow a fully open inside pipe for retrieving the core barrel (Fig. 4).

The merit of this system is that mud pressure within the hole builds up from the sea floor, so that the problem of the fracture gradient being exceeded by the pressure of a mud column extending to the sea surface is avoided. However, considerable development work would be needed to put it into operation. At present the system exists only in concept.

6. Use of a Support Vessel

With the exception of the Antarctic drilling legs the *JOIDES Resolution* has operated independently without a support vessel. One consequence of this mode of operation is that a considerable proportion of the drill ship's time is spent on passage or in port. The addition of a permanent support vessel to ODP could considerably enhance the utilisation of the drill ship, allowing it to remain on site while the support vessel is used to ferry personnel, fuel and supplies between ship and shore. A cost/benefit analysis indicates that employing a permanent support vessel would add about 4% to the overall cost of the programme but could increase the number of drill ship days on site per year by as much as 20%.

The availability of a support vessel would allow much more generous use of drilling muds and chemicals to be employed in reaching target depth. Supplies from the support vessel would augment the limited quantities stored on the drill ship and when required more could be ferried out from shore. This "chemical approach" to achieving target depth would not be a cheap alternative to the engineered systems discussed previously. However, it could allow certain objectives to be achieved without any heavy investment in equipment and without the long lead time required for engineering development.

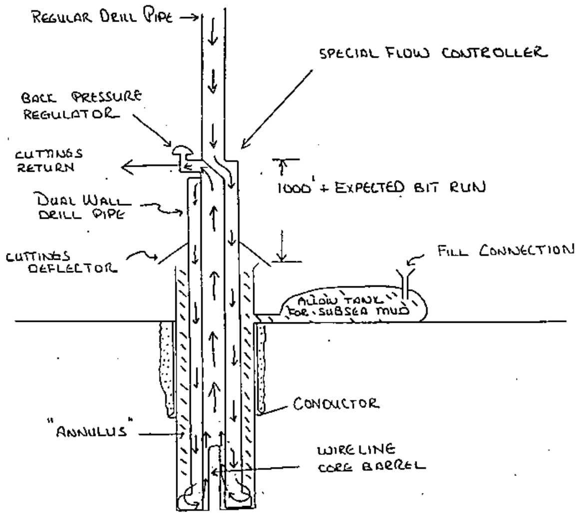

Figure 3. Schematic drawing of dual pipe subsea mud system.

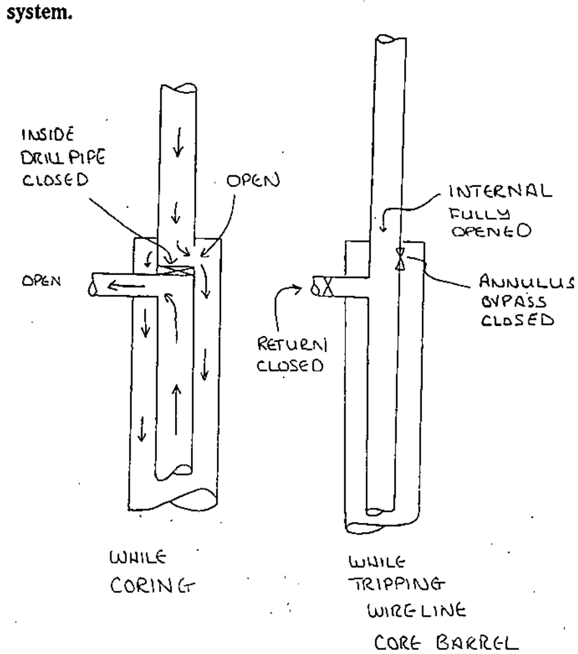

Figure 4. Schematic drawing of the special flow controller required by the dual pipe subsea mud system.

FINANCIAL IMPLICATIONS

In order to assist the scientific ocean drilling community in deciding how engineering development should proceed, four members of the JOIDES Technology and Engineering Development Committee (TEDCOM) have considered the five drilling systems outlined in the previous section with respect to three possible drilling scenarios (Table 2). Case I is representative of a deep sedimentary hole on a passive margin, assumes moderate hole stability and no hydrocarbons. Case II is a deep hole on an active margin that would penetrate the decollement thrust; hole stability problems and slight geopressures are expected. Case III is representative of hydrothermal drilling on zero age oceanic crust. Highly fractured rock and high temperatures would be present, but no sediment cover.

Table 2. Estimated drilling times, probability of success and costs for different drilling scenarios.

SYSTEM	DAILY OPERATING COST ($)	CASE I EAST COAST NORTH AMERICA 4000 m WATER	4000 m PENETRATION	CASE II NANKAI TROUGH 5000 m WATER	4000 m PENETRATION	CASE III EAST PACIFIC RISE 3000 m WATER	3000 m PENETRATION	INITIAL EQUIPMENT INVESTMENT REQUIRED
		Probability of success / Time to reach T.D.	Total cost of hole ($)	Probability of success / Time to reach T.D.	Total cost of hole ($)	Probability of success / Time to reach T.D.	Total cost of hole ($)	($)
ODP PRESENT SYSTEM	82 000	0.25 / 120 days	39.4 M	0.15 / 135 days	73.8 M	0.10 / 100 days	82 M	0 M
18¾" OIL FIELD RISER SYSTEM	162 000	1.0 / 75 days	12.1 M	1.0 / 80 days	13.0 M	1.0 / 95 days	15.4 M	80 M
SLIMLINE RISER	90 000	1.0 / 75 days	6.7 M	1.0 / 76 days	6.8 M	1.0 / 90 days	8.1 M	5.9 M
MINING SYSTEM	86 000	0.35 / 80 days	19.6 M	0.35 / 90 days	22.1 M	1.0 / 125 days	10.7 M	2.9 M
MUD SYSTEM ON BOTTOM	94 000	0.90 / 82 days	8.6 M	0.80 / 88 days	10.3 M	0.90 / 100 days	10.4 M	6.0 M

The probability of success, the time required to reach total depth, and the cost of the drilling operation have been estimated for each drilling system. For some of the systems a substantial initial investment in equipment is required.

In order to put these figures into perspective, it is useful to compare them with the current budget levels of ODP. In FY87, the total cost of the programme was US$ 34.38 M. The operation of the *JOIDES Resolution* consumed 52.4% of this total and the amount allocated for engineering and drilling operations was $ 3.23 M (9.4% of the total). Day to day drilling operations (purchase of new drill bits, coring tools, etc.) consumed $ 2.11 M of this budget, leaving only $ 1.12 M (3.3% of the total) for engineering development. In FY88, the amount allocated for engineering development is only marginally greater, $ 1.18 M, again accounting for 3.3% of the total cost of the programme. It is clear that the sums currently available in the ODP engineering budget are small in comparison with the capital investments foreseen in Table 2. Furthermore, the size of the engineering budget and the manpower available for engineering development are already constraining the rate at which new equipment is being developed.

CONCLUSIONS

Major engineering development must be undertaken if ODP is to be able to meet its scientific objectives. A number of technical concepts are being assessed, ranging from relatively minor modifications of the existing equipment to the acquisition of major new drilling systems requiring heavy capital investment. It is already clear that modifications to the existing ODP system, while yielding useful improvements in certain drilling environments, cannot provide the answers to the major drilling challenges being faced.

While confronted with these challenges, ODP is at the same time frustrated by the present low rate of engineering development. Many important scientific objectives have not yet been attempted because the equipment required does not exist (*e.g.* hydrothermal drilling, deep stratigraphic test holes). The reason for this is clear - too little money is being devoted to engineering development. A disproportionately small percentage of the total cost of the programme is devoted to developing the technology, only 3.3%.

Since 1984, ODP has benefitted from the experience and advice of many expert drilling engineers on the JOIDES Technology and Engineering Development Committee. After reviewing the scale of the problems to be tackled, their judgement, presented to the JOIDES Planning Committee in January 1987 and based on many years of offshore experience, is that engineering development in ODP is seriously underfunded and understaffed. An appropriate level of funding would be about $ 5 M per year and a group of 10 engineers, about twice the present number, should be consigned to the work. However, in order to maintain efficient operation, funding should not increase at more than about 33% per year.

Increased engineering development spending to a more substantial percentage of the total budget would not only allow major scientific objectives to be tackled, but would allow ODP to exploit to the full the excellent suite of downhole measuring tools which are already available.

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Downhole Measurements for the Ocean Drilling Programme

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ABSTRACT

A critical review of well logging technology has confirmed that the logging facilities of the Ocean Drilling Programme incorporate the most advanced suite in the world that is available for routine use. Hitherto unattainable opportunities now exist for using well log data to solve scientific problems of palaeoenvironment, stratigraphy, geochemistry, basement structure, hydrogeology, geomechanics and tectonics. Well log data are a distinct resource base in their own right, they are complementary to laboratory core data, and their continuity often leads to the solution of problems, such as those of cyclicity, which discontinuous core data alone cannot address satisfactorily.

Future enhancements and extensions of the Ocean Drilling Programme's logging capability will, if properly incorporated within the overall programme, allow each borehole to be a true scientific legacy for later generations. Moves towards seismic stratigraphy, and beyond to a more composite event stratigraphy, will parallel advances in wireline geochemical analysis and in formation imaging for facies and structure. Advanced packer tools will contribute to hydrogeological studies of sediments and oceanic basement. Global tectonics will be enhanced by direct and indirect measurements of *in-situ* stress.

In presenting this overview a major objective is the education of the scientific community so that all the potential benefits of a high technology programme of downhole measurements might be fully realized. Experience has shown that this appreciation is not yet sufficiently widespread for the Ocean Drilling Programme to derive maximum benefits from its well logging capability. Furthermore, the conjunctive use of well logs and petrophysical core data constitutes an especially powerful interpretative tool and there is, therefore, a pressing need to upgrade shipboard facilities to allow a commensurate programme of physical properties measurements on core material.

INTRODUCTION

Scientific advancement necessarily follows technical developments in observational capability. For example, the revolutionary advances made by the Deep Sea Drilling Project (DSDP) were derived from a new capability to recover and describe previously unobtainable material from beneath the sea floor. The discoveries made during those early years of research drilling in the oceans were based substantially on qualitative descriptions of core material supplemented by laboratory measurements of chemical and physical properties of spot samples. The volumes sampled were therefore small and the vertical data records were discontinuous.

Earth science is now in the throes of another revolutionary phase, stimulated by important developments in downhole-measurement technology. These developments have made possible accurate in-situ measurements of a broader range of chemical and physical properties. Unlike laboratory measurements on core material, which is irreversibly changed by acquisition, in-situ measurements characterize the environment around the borehole and lead to the determination of chemical and physical properties in that environment. Furthermore, the resulting data in the form of continuous well logs relate to much larger sampling volumes than do core data and thereby provide an intermediate scale between core measurement and geophysics. By using these logs the interpretation of drilling results from the Ocean Drilling Programme (ODP) can be placed on a much sounder quantitative footing than has been achievable hitherto.

CURRENT TECHNOLOGY

The downhole measurement capabilities of the Ocean Drilling Programme fall into four categories: Schlumberger logging tools run on a routine basis, Schlumberger special tools run on request, speciality tools run by Lamont-Doherty Geological Observatory (LDGO), and experimental tools provided by individual scientists within the ODP community. The Schlumberger tools comprise both proven and prototype commercial devices while the experimental tools reflect state-of-the-art technology within the academic and government sectors. Viewed collectively, this assemblage constitutes the most sophisticated and scientifically advanced well logging capability that is being deployed within the world today.

Standard Logging Suite

The routinely-deployed Schlumberger logging suite is described in Table 1, which also indicates the Schlumberger acronym, the principle of operation and the parametric objective(s) of each tool. The standard suite comprises three tool combinations, each of which requires a dedicated logging run.

Additional Schlumberger Logging Tools

Three other Schlumberger tools are available aboard ship with a fourth (SAT) being available for specific legs. These tools are described in Table 2.

Table 1. Standard shipboard logging tools

Combination/tool	Schlumberger acronym	Principle of operation	Parametric objective
Seismic-Stratigraphic			
Full Waveform Sonic	SDT	travel-time of sound (eight receivers)	Sound velocity and attenuation (compressional and shear)
Dual Induction	ILD	induced current (deep sensing)	Conductivity (resistivity)
	ILM	induced current (medium sensing)	Conductivity (resistivity)
Spherically-Focussed	SFL	alternating current (shallow sensing)	Resistivity
Gamma-ray	GR	natural gamma ray emissions	Gamma count rate
Caliper	CAL	electrical monitoring of mechanical gauge	Hole diameter
Litho-porosity			
Neutron	CNT-G	slowing down/absorption of neutrons from moderate energy source	Porosity
Spectral Density	LDT	scattering/attenuation of gamma rays	Bulk density (porosity) Photoelectric absorption factor
Natural Gamma Spectral	NGT	natural gamma ray emissions	Total gamma count rate plus constituent count rates for Uranium/Potassium/Thorium
Geochemical			
Induced Gamma Spectral	GST	gamma-ray emissions from slowing-down/ absorption of neutrons from downhole accelerator	Gamma-ray energy spectrum (elemental analysis)
Aluminium Activation	AACT	gamma-ray emissions from slowing-down/ absorption of neutrons from low energy Californium source	Gamma count rate windowed for aluminium (elemental analysis)
Natural Gamma Spectral	NGT	natural gamma-ray emissions	Total gamma count rate plus constituent count rates for Uranium/Potassium/Thorium

Table 2. Additional Schlumberger logging tools

Tool	Schlumberger acronym	Principle of operation	Parametric objective
Dual Laterolog	LLD	alternating current (deep sensing)	Resistivity
	LLS	alternating current (shallow sensing)	Resistivity
General Purpose Inclinometer	GPIT	orientated magnetic field and inclination	Vector components of magnetic field Hole azimuth and direction
Well Seismic Tool	WST	travel-time of sound between surface shot point and wellbore geophone : single-component waveform	Sound velocity Depths to reflecting horizons VSP (single-component)
Seismic Acquisition Tool	SAT	as above but with three-component waveform	VSP (three-component)

LDGO Speciality Tools

There are three speciality tools operated on board ship by LDGO staff.

Borehole Televiewer

The borehole televiewer (BHTV) transmits an ultrasonic pulse from a centralized position in a wellbore and receives the pulse reflected from the borehole wall. The returning signal is analysed for amplitude which is displayed as brightness on a three-axis oscilloscope. The oscilloscope image is therefore an acoustic picture of the reflectivity of the borehole wall. The BHTV data can be processed to obtain an image in which the intensity is proportional to the travel time of the reflected pulse. This travel-time log yields a three-dimensional image of the shape of the borehole as a function of depth and azimuth, thereby producing a 360° caliper log.

Multichannel Sonic Tool

The multichannel sonic tool is a single-source, twelve-receiver array in which the receivers are 15 cm apart beginning 1, 2 or 3 m from the source. The source emits a compressional pulse from a centralized position in the wellbore and records twelve sonic wavetrains in digital form. These waveforms can be analysed to yield compressional and shear velocities, and variations in frequency content and amplitude, thereby allowing a characterization of the elastic properties of the formation.

Wireline Packer

The wireline packer, to be introduced in 1988, isolates a one-metre section of the borehole by means of two rubber packers inflated against the wellbore using a downhole motor. Borehole fluid is then drawn into a sample chamber where calcium content, resistivity, pH, temperature and pressure are monitored and the data relayed to the surface. When sufficient

Table 3. JOIDES experimental tools

Tool	Development group
Advanced Piston Coring - Temperature	Texas A & M University, USA
High Resolution Temperature Probe	BGR, Fed. Rep. of Germany
High Temperature Probe	BRGM, France
Barnes-Uyeda Temperature/Water Sampler	University of Washington, USA ; University of Tokyo, Japan
Barnes-McDuff Temperature/Water Sampler	University of Washington, USA
Kuster Water Sampler	Texas A & M University, USA
Pressure Core Barrel	Texas A & M University, USA
Large-Scale Formation Resistivity	University of Miami, USA
Three-axis Magnetometer	Japan
Three-axis Gyro Magnetometer	US Geological Survey
Three-axis Magnetometer	University of Washington, USA
Three-axis Gyro Magnetometer	BGR, Fed. Rep. of Germany
Susceptibility	University of Munich, Fed. Rep. of Germany
Susceptibility	US Geological Survey
TAM Rotatable Packer	Texas A & M University, USA
TAM Straddle Packer	University of Miami, USA
Oblique Seismic Experiment (3 axis)	Woods Hole Oceanographic Institution, USA
Oblique Seismic Experiment	Hawaii Institute of Geophysics, USA
VSP (Well Seismic Tool - 1 axis)	University of Texas at Austin, USA
VSP (Galperin - 3 axis)	University of Texas at Austin, USA
Wireline Re-entry	France

formation fluid has been drawn in to purge the borehole fluid, a sample is taken. Four samples per tool lowering can be taken.

JOIDES Experimental Tools

These are provided by individual scientists or institutions within the ODP community. The tools are run on a non-routine basis according to their potential contribution to the scientific objectives of a leg and, of course, their availability. Offset VSP, temperature, flow, susceptibility, ultra-long-spaced resistivity and packers are among those tools that have been used in ODP (Table 3).

Aspects of Tool Response

Nearly all logging tools respond primarily to mineralogy and porosity (in the absence of hydrocarbons). The determination of porosity from logs inevitably requires a knowledge of the mineralogy. With the logging tools currently available, one can invert log responses and solve for the percentages of all minerals present in amounts greater than about 5%. The principal complication to such an inversion is that some clay minerals vary in composition (and therefore log response) as a function of both depth and locale ; these variations degrade the accuracy of mineralogy determination from logs.

The usefulness of individual logs in evaluating mineralogy and porosity in different downhole environments also depends very much on the vertical resolution of the logging tools. This varies from a few centimetres to over a metre according to the physical principles and configurations of the different measuring systems. Most logging tools have a vertical resolution of about 0.5 m, *i.e.* a bed of thickness less than 0.5 m would not manifest itself sufficiently in logging tool response to be characterized. Logging tools with vertical resolutions as high as 1 cm are now commercially available, but slimhole versions suitable for ODP use have not yet been developed. Resolution can also be enhanced by signal processing.

Logging tools provide a complete and representative response to changes in formation characteristics by sampling every 15 cm over the entire logged interval, regardless of lithology. In contrast, the effectiveness of core recovery is often controlled by those same formation characteristics, so that the degree of core recovery can be partially a function of rock type. Furthermore, in alternating lithologies, preferential core recovery of one lithology may give a non-representative sample. Core recovery averages 94% for hydraulic piston cores (usually the top 100-150 m) and 46% for rotary cores : of this amount, a significant proportion is disturbed and mixed by the drilling process.

APPLICATION OF DOWNHOLE MEASUREMENTS TO SPECIFIC SCIENTIFIC TOPICS

This review of the rolè of downhole measurement technology in addressing the scientific objectives of ODP has been organised along the lines of the five topics which are providing the technical framework for the Second Conference on Scientific Ocean Drilling (COSOD II).

Global Environmental Changes

Rhythmic, cyclic and long-term environmental changes recorded in the mineralogy or grain size of marine sediments can be recognised in modern well logs provided that the sedimentation rate is sufficient to produce resolvable events. Logs are especially well suited for addressing problems of environmental change since the solutions frequently require a continuous stratigraphic record in order that the effects of variations in climate and ocean circulation upon sediment composition and texture can be recognised. Improvements in stratigraphic resolution should be most achievable through the combined use of seismic information, diverse well logs and bio- and lithostratigraphic data from core studies. The use of core data alone is not defensible for these are rarely sufficiently continuous.

Mantle-Crust Interactions

Downhole measurements including wireline logging and special borehole geophysical experiments have already played a major role in furthering our knowledge of oceanic crustal structure. Logging is an essential element of crustal drilling programmes because it provides a complete record of physical properties in the borehole, in contrast to the very sparse (25%) recovery of core material in hard rock. Borehole geophysical experiments expand the scale of the information acquired from the borehole from a few metres to a few hundreds of metres or kilometres, which is the scale of typical marine geophysical surveys. In sedimentary sequences it is common to assume that the structure intersected by the borehole and sampled at a lateral resolution of less than a metre extends horizontally for at least hundreds of metres. This assumption is not valid in oceanic crust, where strong lateral heterogeneities can occur over length scales from centimetres to kilometres.

Fluid Circulation and Global Geochemical Budget

Drill holes provide unique opportunities to obtain invaluable data on the depth pattern of fluid flow and the physical properties that control them in oceanic sediments and crust. By carefully applying currently available logging and experimental technology in ODP holes, reasonable estimates can be made of vertical flow rates and the two critical controlling properties, porosity and permeability.

Stress and Deformation of the Lithosphere

The ODP's well logging and downhole measurements programme provides continuous records of information which, in turn, permits fine-scale hole-to-hole correlation of physical and chemical parameters pertinent to an improved understanding of the lithosphere. For investigations which involve documenting and accounting for brittle and ductile deformation of the lithosphere, three categories of information are available : data for establishing the tectonic history of the drillsites and their surrounding areas, data bearing on the physical properties of the drilled section, and indications of ongoing tectonic activity.

Table 4. Operational high-temperature logging tools

Tool/equipment	S	U	LA	J (a)
Natural Gamma Spectral		x		
Density	x	x		
Neutron	x	x		
Self Potential (SP)		x		
Induction	x			
Resistivity		x		
Sonic	x	x	x	
Seismometer			x	x (b)
Borehole Televiewer		x	x	
Caliper		x	x	x
Temperature	x	x	x	x
Pressure				x
Flow	x	x	x	x
Water Sampler		x	x	
Explosives			x	
Cable	x	x (c)		x (d)

S : Schlumberger (260°C) ; U : USGS (310°C) ;
LA : Los Alamos (310°C) ; J : JAPEX (450°C)

(a) up to 3 hours, 3 km depth
(b) microphone and accelerometer
(c) TFE
(d) MgO

Evolution and Extinction of Oceanic Biota

Downhole geophysical logs have yet to contribute substantially to the study of the evolution and extinction of oceanic biota in ODP. Logs have contributed only indirectly through their detection of environmental change in the sedimentary column. This approach to the history of biotic events is achievable through well logging provided that three important conditions are met. Firstly, the emergence of a marine organic community, changes in its diversity, and its ultimate disappearance must be attributable to physical and chemical processes or other environmental factors that are manifested in the oceanic sedimentary record. Secondly, these diagnostic physico-chemical characteristics of sediments must be sufficiently distinctive in terms of electrical, nuclear or sonic properties that environmentally-governed sedimentary zones can be recognised definitively. Thirdly, the time scales must be such that the characteristic sediments are sufficiently thick to be resolved by contemporary logging tools.

FUTURE TECHNOLOGY

As stated earlier, the logging tools deployed within ODP constitute the most scientifically advanced well logging capability that is in regular use within the world today. Nevertheless, major upgrades and new capabilities are needed to take full advantage of the holes drilled in the future. These enhancements fall into six categories.

New Tools and Upgrades

A variety of new tools are being developed which would improve the accuracy of our present measurements or give the programme entirely new capabilities.

Wireline Packer

Geochemical studies in ODP would be greatly enhanced by the ability to collect uncontaminated pore water samples. A fluid sampling capability might be developed for application with the drillstring packers. The acquisition of the wireline packer, modified for ODP use, will go far towards meeting this goal. If a sufficiently robust packer can be developed, hydraulic fracture *in-situ* stress magnitudes could be measured ahead of the bit.

Borehole Imaging

Much structural and tectonic information could be acquired if ODP possessed a satisfactory capability for imaging borehole walls on a routine basis. The orientation of faults, joints and bedding and the principal directions of stress could be readily determined using a variety of tools under development such as the digital borehole televiewer and the slimhole formation microscanner. This would have profound implications for testing tectonic models.

Mineralogy Tools

Mineralogy can be evaluated downhole through nuclear spectral logging using the geochemical tool combination (Table 1). This evaluation requires, inter alia, an assumption about the elemental domain. Usually this assumption is made on the basis of the elements actually detected plus carbon and oxygen. If other elements are present, the inferred mineralogy will be incorrect. A new generation of cryogenic tools with high resolution germanium detectors will allow a more comprehensive evaluation of constituent elements. This will make it possible to scan a succession for mineralogical gradients and discontinuities which could never be recognized either by conventional nuclear spectral devices or through the laboratory analysis of discrete core samples.

Borehole Gravimeter

It is important to make accurate measurements of porosity in basement because porosity controls properties such as velocity, resistivity and permeability. The conventional use of nuclear tools to determine porosity is hindered by calibration difficulties for hard rock. Extremely accurate values of porosity can be determined using formation densities obtained from borehole gravimetry in conjunction with grain densities from core. Tools are currently being developed which are sufficiently small in diameter for ODP use.

Measurement-while-Drilling

The incorporation of petrophysical sensors in the drill string allows very rudimentary logs to be recorded during the drilling process. Although the measurement technology is sophisticated, the tool configurations and measurement capabilities correspond to the wireline technology of the early 1950s. Nevertheless, by taking advantage of this technology ODP could acquire a limited suite of logs in all holes, including shallow and unstable holes, at no extra cost in terms of drilling time. This would provide basic petrophysical coverage of those intervals which cannot subsequently be logged by wireline.

Mechanical Properties

The ODP currently has no means of directly measuring the mechanical and engineering properties of sediments downhole. By modifying self-boring and push-in tools developed by the geotechnical industry, it should be possible to measure pore pressure, shear strength, compressive strength and other properties needed to define models of sediment compaction, lithification and deformation.

High Temperature Measurements

As drilling extends to greater depths in oceanic crust or is carried out in anomalously hot environments near hydrothermal vents or active magma chambers, special logging tools will be needed which can withstand high temperatures. Although a small number of tools have been developed which can operate for a few hours at temperatures up to 450°C using dewars and heat sinks (Table 4), only the temperature-measuring tools can operate for long periods. Several alternative design strategies for routine high-temperature logging tools are under study, and these include the use of exotic high temperature semiconductors, vacuum substrates and optically (as opposed to electronically) interrogated sensors. In particular, the temperature ratings of the APC-temperature tool and of the available temperature/pore pressure/fluid-sampling tools (Table 3) need to be upgraded. Furthermore, the programme needs packer inflation elements for use at temperatures above the normal operating limits of 100-120°C. The benefits of high temperature tool developments would be considerable because for the first time it would be possible to examine and log those active high temperature environments in which oceanic crust is created.

Wireline Re-entry

A major problem has turned out to be time competition between drilling and wireline well logging within the overall constraint of a leg of fixed duration. A possible compromise might be to design the principal drillholes for wireline re-entry. Then the logging suites could be run during the leg itself but the more time-consuming borehole surveys such as VSP could be deferred to a subsequent visit, perhaps by a second ship. This possibility logically leads to the subject of downhole observatories.

Long-Term Observatories

The concept of long-term physico-chemical observatories beneath the sea floor embraces one of the most exciting potential uses of ODP boreholes. A modest start towards placing geophysical instrumentation in boreholes was made during DSDP with the installation of battery-powered seismometers in the sea floor off Mexico, Guatemala, Japan and the Tonga Trench. In most cases these instruments could only operate for two months before the batteries had to be replaced. The long-term goal should be to develop an array of tools which can operate indefinitely at high temperatures. This will require a multi-national effort involving high technology. Some examples of the uses of long-term geophysical and geochemical observatories are listed below.

(i) The measurement of temperature, pressure, hydrothermal circulation and water chemistry in a borehole long after drilling has ceased and the borehole has returned to equilibrium.

(ii) The detection and recording of intermittent events such as submarine eruptions, the birth and death of hydrothermal vents, the passage of particle plumes, and deep sea current "storms" which might occur only once or twice in a decade.

(iii) The installation of an array of seismic and magnetic observatories beneath the sea floor to complement existing arrays on land. For example, three-component seismometers clamped within the crust provide sufficiently high quality data to infer seismic anisotropy from particle motions. Seismometers resting on the sea floor are not sufficiently well coupled for this type of analysis to be useful.

CONCLUSIONS AND RECOMMENDATIONS

The Scientific Legacy of ODP Holes

An ODP borehole is a scientific legacy : it is not a mere relic of a core acquisition procedure. Scientific measurements in boreholes and on recovered core should be planned on the basis of their incorporation into a regional or global model, their future reinterpretation and, in some cases, the reoccupation of the drill site for further investigations.

The Nature of Log Data

Core recovery is discontinuous and represents a small volume of sampled material. Core data are often used to calibrate the interpretation of wireline logs. Wireline well logs provide a continuous record of the succession and sample a volume about 100 times greater than that of recovered core. The cost of well logging is small compared to the expense of drilling an ocean-bottom hole in the first place. In terms of cost-effectiveness and the volume sampled, well logging programmes produce substantial returns.

Worldwide Status of Well Logging

Well logging is not a replacement for core analysis nor is it a subordinate discipline. It provides complementary information which is often of a different type from that which can be determined by core analysis. Logging is not therefore a luxurious add-on to a drilling programme. It is an integral part of data acquisition within any deep drilling programme and has a specific and important role of its own. This premise has been proved time and time again outside ODP, at sea or on land, in pure geophysics or in the mining and oil industries.

Status of Well Logging within ODP

Although the logging tools deployed on board ship constitute the most advanced suite in the world today that is available for routine use, the facility is not being extensively deployed within ODP holes. Much drilled footage is never logged. This extraordinary situation is contrary to scientific practice in sister disciplines.

Logging Footage

The shortfall in ODP logging footage is attributable to a blend of scientific, planning, and operational factors. If this unsatisfactory state of affairs is to be improved, a prerequisite is better education of the earth science community in the scientific uses of well logs. A second requirement is the realistic scheduling of practically-realizable drilling objectives so that logging operations are not sacrificed in an effort to attain the maximum drilled footage. The problem is compounded by the necessity to log last at each site, which inevitably means that where drilling is over-programmed, the logging schedule is truncated or not done at all. *Too many holes, inadequately studied, are less useful than fewer holes investigated thoroughly.*

Several operational factors are noteworthy. ODP must drill loggable hole : bridging, cave-ins, stuck core barrels and jammed bits have all contributed to the loss of logged intervals. Mud systems which prevent clay swelling, efficient use of the side-entry sub and logging through pipe are three potential improvements. Finally, there is the question of scientific priorities during the legs themselves. The arbitrary exclusion of well logging activity once at sea might appear justifiable to a few immediately involved proponents of additional core acquisition but to the community at large, and to future generations, it is a gross misuse of responsibility.

Benefits of ODP Well Log Data

If the difficulties expounded in the previous section can be overcome, the prospects for the scientific interpretation of well log data are indeed exciting. The first key benefit is the control of seismic stratigraphy, emphasising the integration of sub-disciplines and the reconciliation of different scales of investigation, both of which are characterizing earth science in the Eighties. A second major benefit is in the area of downhole geochemical analysis with the capability to log elemental abundances. This, in conjunction with the other "standard" tools, allows a comprehensive physico-chemical characterization of the succession for mineralogical, sedimentological or structural purposes. The continuous nature of the logs provides a stratigraphic resolution that is often not possible with discontinuous core data. A third major benefit is in the improved determination of porosity and permeability for hydrogeological purposes. Finally, there are the geotectonic benefits that stem from a capability to measure principal stress directions through breakouts. Ultimately one can envisage constructing a world stress map to test what really drives plate tectonics.

Future Benefits of ODP Logging

The biggest drawback of the ODP standard logging suite (Table 1) is that it does not contain a dipmeter or even a single pad micro-resistivity tool with high vertical resolution. The most advanced multipad microresistivity tool is the formation microscanner (FMS) which requires miniaturization before it can be deployed in ODP holes. Once this has been done, it will be possible to obtain a high resolution electrical image of the borehole wall which will aid in facies identification, basement structure evaluation, fracture recognition and the study of tectonics.

Another major benefit in the future will be the introduction of high-spectral-resolution cryogenic detectors in induced gamma spectral tools. It should then be possible to detect a wider range of elements from neutron activation, for example chromium, nickel, manganese and vanadium. However, because the high resolution detectors are less efficient than their low-resolution counterparts (*i.e.* they need to count induced gamma rays for longer time periods in order to attain the same sample statistics), the cryogenic tools might be used alongside the existing devices rather than displace them. Whatever the outcome, the outlook for downhole geochemistry looks extremely promising.

A third future prospect is a revised concept of stratigraphy embracing the integrated use of micropaleontology, petrophysics including downhole geomagnetics, lithology, isotope geochemistry and geoseismics. Such an integrated approach to stratigraphy would allow a much finer event resolution than biostratigraphy alone can provide. Hitherto, non-biostratigraphic data have been underutilized for dating and correlation purposes.

Laboratory Physical Properties

There is an urgent need to upgrade the shipboard laboratory measurement of physical properties such as acoustic velocity, natural radioactivity and electrical resistivity. Shipboard acquisition of these data is important because they provide a petrophysical data base to complement the laboratory petrochemistry. Furthermore, all of these petrophysical data have an equivalent downhole measurement and they tie core to their precise location within the logged section. The conjunctive use of core data and logs is an especially powerful interpretative tool.

Improved output of laboratory petrophysical data cannot be achieved without a commensurate upgrading of core handling and preservation procedures. For example, it will be necessary to take horizontal core plugs on board ship before the core is split. The plugs should be stored in saline water to prevent dehydration, for it is known that rock physical properties change on drying. Similarly, the split core should be properly preserved so that follow-up operations on land can be pursued meaningfully.

These comments are given a greater poignancy by recent developments in wireline coring technology. Logging coupled with wireline sidewall coring can allow holes to be drilled without continuous coring where necessary, for example in ultra-hot environments or on legs where many deep-penetration holes are required to be drilled quickly.

Epilogue

Well logging technology is changing continuously in the world today. Within ODP the logging scenario has got to change much more markedly to do justice to the high technology currently available to the programme. This high-technology capability is being underutilized as, too, is the opportunity for commensurate physical-property measurements in shipboard laboratories. Unless action is taken to improve the present situation on the planning, operational and scientific fronts, much potential information will be lost for posterity. It is hoped that this paper will stimulate appropriate measures by generating an improved appreciation of the scientific value of well logging and its potential for the future.

Alternate Platforms

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ABSTRACT

The use of a specialized vessel to supplement the single ODP drillship offers many advantages. It would relieve pressure from the presently very busy schedule of the *JOIDES Resolution* as well as help provide the right tool for the right task.

A "station vessel" equipped with aluminum drill pipe and powerful pumps could perform HPC coring, logging and downhole instrumentation, and hard rock shallow penetration coring, for example, as well as other programs not directly related to ODP.

A pilot study conducted in France has clearly demonstrated the feasibility of such a project both in terms of technology and economics. The construction costs of the platform would not be part of the ODP program and the increase of operational costs over current ODP costs for a part-time use of the ship appears rather minimal in regard of the many advantages of this new approach.

INTRODUCTION

Technical developments achieved within the framework of the Deep Sea Drilling Project (DSDP) and the Ocean Drilling Program (ODP) have vastly improved our access to the ocean subbottom on a global scale. A new suite of tools in particular has opened entirely new fields in earth sciences. Paleoceanography, for example, has developed in an unprecedented fashion based on the use of the Hydraulic Piston Corer (HPC). Logging and other downhole instrumentation have become an essential component of the drilling program.

Because of the multiple tasks to be accomplished with the ODP drillship, however, it has become increasingly difficult to accommodate many of the high-priority objectives proposed by JOIDES. Increased international participation, together with the rapid development of new concepts that need testing, has naturally overloaded the drilling program to such an extent that in many cases there is no time to capitalize on many of the results in an efficient manner. One can safely state that the ODP ship is actually uncovering many more scientific problems than it can solve.

As a consequence, the need has arisen for a supplementary approach and the idea that some other platform than the very busy *JOIDES Resolution* should be considered to supplement its work has recently emerged as a very attractive option within the marine geoscience community both in France and in Europe, as well as in the world at large.

Such an option could obviously present many advantages over the present "single ship" mode of operation. To name a few :

- It would relieve pressure from the schedule of the *JOIDES Resolution* and also provide badly needed time to concentrate more on problem-solving operation (ship time would be essentially twice what it is today).
- It would help adapt more precisely the tool to the task, which has technical as well as economical advantages.
- It would improve technological development programs (for coring techniques naturally but more specifically for downhole instrumentation) by :
  - allocating substantial ship time for such programs,
  - bringing more personnel, more expertise and more funding from participating countries in direct contact with downhole experimentation.

In the meantime, looking ahead for further developments of a modern oceanographic fleet, the French community, in consultation with various scientists in Europe and in the US, has examined various possibilities and requirements for a "station vessel" capable of handling heavy equipment near, at and beneath the seafloor. From these considerations emerged the concept of a dynamically positioned ship equipped with a conduit (drill pipe) and capable of delivering power at depth (hydraulic pumps).

The "conduit and pump" combination represents a simplification of a drilling vessel and would place the new platform roughly somewhere between an *Alcoa Seaprobe* type and a *Glomar Challenger* or *JOIDES Resolution* type. It would essentially be capable of :

- *hydraulic piston coring* (HPC) sediments down to "refusal" (that is about 250 meters below the sea-floor as an average) ;
- *logging* and instrumenting DSDP and ODP drill holes. Using the drill pipe as a conduit for the instruments, as a means to help them pass through bridges into the hole, as a fluid sampling system (packer) and as a way to deliver hydraulic power to activate systems whenever necessary ;
- *turbo-coring hard rock* (with a "Navidrill" type of coring device) either outcropping or covered by a relatively thin (less than about 250 meters) sediment cover. A core of approximately 20 to 25 meters in length could be taken in hard rock in one shot (since this is not a wireline operation, it requires a full round trip of the drill pipe) ;
- launching, activating, controlling and retrieving bulky *long-term seafloor observatories* and heavy sampling devices ;
- making highly detailed *visual* (TV, photography) and *geophysical* (near-bottom seismics, magnetometry, etc...) *surveys* of the seafloor and subsurface in the vicinity of drill holes at a scale of the order of a few tens to a few hundred square miles.

SEDIMENT CORING : HPC GLOBAL ARRAY

The report of COSOD II Working Group 1 emphasizes how the study of the sediment record of the oceanic basins on a global scale can lead to tremendous advances in our understanding of the evolution of the ocean system in the history of our planet. This approach is at the root of the development of new "whole earth" concepts that provide a link between the *geophysical*, *tectonic*, *volcanic*, *oceanographic*, *atmospheric*, and *biologic* components of the history of the earth.

If data at hand clearly demonstrate the validity of various mechanisms, they are grossly insufficient to provide solutions to problems posed by the modeling of the entire system. The ODP style of drilling is not well adapted to the study of high- and very high-frequency changes, at scales of the order of 100 to 10 000 years, because such an approach requires very extensive recovery of high-resolution (HR). to very high-resolution (VHR) stratigraphic sequences. This can be accomplished only by HPC coring at a very large number of sites distributed along a series of transects all over the surface of the earth, in key areas representing a wide range of environments, water depths, and latitudes. If a single ship such as the *JOIDES Resolution*, operating in the present mode where many other deep drilling objectives have to be considered, were to be used for that purpose, it would obviously take tens of years before such studies could be completed. One can also ask the question if it is reasonable to use that drill ship, part-time, for work that could be accomplished as well from a dedicated platfom that would be much more economical to run.

In addition to the paleoceanography-paleoclimatology project an extensive program of HPC coring appears essential in order to study in great detail major sedimentary features such as "sediment drifts" accumulated under various current regimes, slope and rise sediment bodies resulting from major mass wasting processes, as well as the history of turbidite deposition (deep-sea fans in particular) in relation to sea level and tectonics.

LOGGING AND DOWNHOLE EXPERIMENTS

During the last phases of DSDP and with the advent of ODP, the value of sophisticated downhole experimentation has been widely recognized. Yet limited ship time availability and relatively few technical innovations have kept these aspects of the program at a rather secondary level. Despite the strong involvement of a specialized group (the BRG of Lamont-Doherty Geological Observatory), the pressure to "drill hole" is certainly as strong as, or stronger, than ever and on many legs the logging program still has to be imposed on the scientific party. It is still viewed by many as something that "must" be done without a real understanding of its scientific value. This general situation prevents both the implementation of a fully efficient conventional logging program and the development of new experiments. The availability of another platform that would allow reoccupation of drill sites and short- or long-term downhole experimentation would certainly change the perspectives for a real full scale program.

One of the main advantages of the use of another platform in this respect would be the possibility to conduct more easily long-term experiments by allowing a ship (at a much lower cost than the drilling vessel) to stay on, or to come back periodically to a given site for extended periods of time.

Another advantage of this approach would be to encourage a wider participation of scientists and technicians from various member countries in that aspect of the drilling program. Whereas conventional logging should undoubtedly be run by a contracted operator such as the BRG at LDGO, the development of new concepts and tools would benefit tremendously from a broader direct participation at sea. Admittedly, nothing at the present time prevents any interested investigator from submitting a proposal to JOIDES and conducting experiments on the *JOIDES Resolution*. There is no doubt, however, that it is by repeated and more direct confrontation with the experimental aspects of the work that new concepts can emerge. At this time, time limitations do not encourage a generalized effort by a large community of investigators along these lines. Yet interest, expertise, and funding for that purpose could be made readily available in several countries participating in ODP. The advent of another platform with realistic time allocation for experimentation within drill holes would certainly improve drastically the value of many ODP and DSDP sites.

HARD ROCK CORING

Sampling of basement rocks in oceanic basins has been accomplished over the past years by dredging outcrops, drilling through the sediment cover, and more recently by drilling directly into the basement without sediment cover. Because of the geodynamic evolution of the oceanic lithosphere, it is clear that direct access to basement rocks is generally limited to very young oceanic crust present near the crest of active oceanic spreading centers. Only drilling gives access to oceanic crust older than a few 10^4 to 10^6 years. In the recent past, investigation of the oceanic crust, by drilling as well as by direct observation through submersibles, has been concentrated on ridge crest areas and accretion-related processes. Drilling, in that respect, has proven an exceptional tool to investigate the deeper nature of the oceanic basement. One single deep hole (504B, on the Galapagos spreading center) has provided us with the first direct sampling of deeper layers of the oceanic crust. Reaching more than a kilometer beneath the top of layer 2, thus penetrating deeply into the "transition" zone of layer 2A and approaching layer 3, this hole has become a natural laboratory, and rock sampling has been accompanied by seismic, thermal, geochemical, hydrological and other experiments. This has been accomplished through a very persistent approach combining up to five DSDP and ODP cruises, and the effort may be continued for several years. It does not appear economical nor practical to devote months of *JOIDES Resolution* time to run downhole experiments at such a site. A specialized vessel would be much more appropriate for the task and the heavy drillship should be used only for deepening the hole.

"Bare rock" drilling has started recently and has helped obtain some geographical coverage of the nature of basement rocks in various ridge crest settings. Although at the present time it has failed to reach more than a few tens of meters into the top of the young oceanic crust, it does represent a necessary approach to understand lateral variability of the composition of that crust. And of course the set of DSDP and ODP holes that have reached basement beneath oceanic sediments and achieved limited penetration into it have provided an interesting but limited view of the petrological and geochemical nature of the oceanic crust on a global scale.

Many problems are being posed that require more extensive lateral coverage. If it appears that the *JOIDES Resolution* is ideally fitted for attemps at deep to very deep penetration into the oceanic basement, then extensive "geographical" (lateral) coverage could be best accomplished through the use of a coring ship equipped with "single shot" turbo-coring capability that could quickly and economically provide a detailed global picture of the variability of the oceanic crust by reaching a few tens of meters into the top of layer 2 in various settings such as slow, fast, and very fast spreading centers, and along transects ranging from "zero age" to crust older than a few million to a few tens of million years (that is beneath sediment cover of a few tens to a few hundred meters). One of the most important results that could be gained from such an approach would be the actual mapping of geochemical variations in the composition of oceanic basalts that are believed to represent the surfacial expression of mantle heterogeneities.

The ridge crests and flanks do not represent the only place where mantle studies can be conducted. Recent work along passive continental margins has provided models that envision mantle "denudation" caused by extension tectonics and stretching of the outer edge of the continental crust. Outcrops of mantle rocks in these settings are rare but they have been investigated along the Iberian continental margin.

"Subcrops" of such rocks have been recognized on seismic profiles. They are present beneath a few tens to a few hundred meters of sediment along the base of several passive continental margins. There again geographical coverage is the key to our understanding of lateral variability in the geochemical composition of the mantle, which in turn is the key to our understanding of its heterogeneity and dynamics (what is the size of "mantle heterogeneities" ? How long do they last ? etc).

NEAR-BOTTOM AND SEAFLOOR EXPERIMENTS AND LABORATORIES

Today almost all near-bottom observations and seafloor experimentation are conducted either with submersibles (manned or unmanned) or with wireline techniques. Submersible operations are relatively expensive whereas wireline techniques often lack precision in the positioning. Both approaches suffer from lack of power at the site of experimentation and, at least for the submersibles, have important weight limitations.

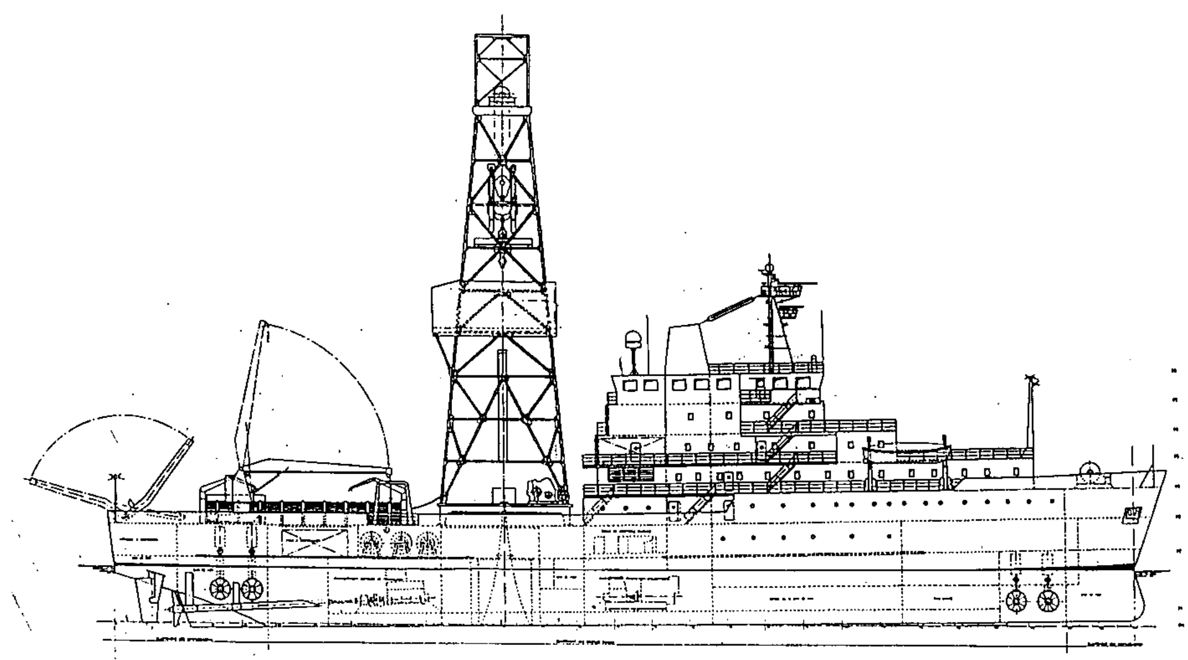
A dynamically positioned vessel equipped with a pipe that can be lowered to the seafloor could represent a new approach that would economically supplement these techniques. The pipe represents not only a conduit through which sampling devices and other instruments can be lowered and recovered but also, when coupled with pumps, it brings to the seafloor a power supply that exceeds that of most other systems. It can also be equipped with heavy equipment and video systems, it can be precisely navigated at slow speeds (in the order of 1 knot) and connect and disconnect with a variety of seafloor installed observatories, utilizing the re-entry technique. It would be capable of sampling sediment as well as fluids in a variety of precisely located environments. It could precisely position, launch, orient, activate long- and short-term observatories, interact with them (and retrieve data for example) on a regular basis. The lower end of the pipe can be equipped with such a variety of sensors, most of them transmitting data through optical fiber lines, that imagination only will set limits to its capabilities. In a sense, to use a space research analogy, the ship and its pipe would represent the launching system whereas laboratories and sensors would be equivalent to satellites and unmanned space stations. Re-entry would provide a periodical physical link with seafloor systems, bring power and instructions, and retrieve data.

HOW REALISTIC, TECHNICALLY, ECONOMICALLY ?

The "station ship" described here is not specifically designed for the exclusive use of the ODP program. It is primarily a means of interacting directly, with power, with the seafloor and the subsurface of the deep ocean. A variety of research programs can be envisioned around such a tool (deep sea biological experimentation, hydrothermal monitoring, geophysics, waste disposal experiments, mineral resources assessment, etc). The three main research opportunities offered by this type of platform, however, appear to suplement extremely well those of the present Ocean Drilling Program (HPC coring, logging and downhole experiments, and hard rock composition mapping).

A few years ago a pilot feasibility study was conducted in France by IFREMER. It involved a major shipbuilding company and a major offshore drilling company. The results showed that such a ship could be designed and built for a cost comparable to that of the most modern conventional oceanographic vessels (the new *METEOR* for example) and that it could also be run at costs comparable to, or very slightly (less than 20%) more than that of the large conventional research ships in existence today, that is less than US $ 20 000 per day.

The programming of the ship during the time it would be used for operations falling within the objectives of ODP, especially as redefined by COSOD II, would have to be closely coordinated within the JOIDES advisory structure. At this time it seems that if the construction cost of the vessel were entirely supported through an initiative totally separate from ODP, the yearly increase in operational costs of the drilling program itself would be rather limited. For example, devoting 50% of the new ship's time to ODP would result in a total increase of 19% over the present cost of the drill ship operation, whereas the corresponding benefit in terms of scientific returns appears enormous in regard to this small investment. One can imagine a variety of operational scenarios that would maximize these returns. The global array of HPC transects could be easily combined with geochemical and petrological mapping of basement rocks as well as logging and



downhole experiments. For example, the *JOIDES Resolution* could drill a series of deep to moderately deep holes and equip them with re-entry mini-cones. Then the lighter vessel could sweep through the previously drilled region and perform logging at these sites plus any other type of downhole experiments, and, between these sites, it could run a complete HPC and hard rock surface sampling program.

The very preliminary design given here only represents *one example*, resulting from that study. The ship depicted is 99 meters in length with a displacement of 4400 tons. It is equipped with a dynamic positioning system, a moonpool, a derrick fitted with an in-line heave compensation system, a pipe racking system and conventional pumps. It carries 4500 meters (which could be extended to 6000 m on a slightly larger version) of aluminum pipe. The vessel would travel light and be ballasted with sea water when on station. If necessary the derrick and pipe rack could be removed within approximately two weeks and the vessel could be quickly returned to a more conventional utilization.

Updating of this design and more accurate cost estimates are being performed at the present time. So are negotiations with various European partners about different tools to be designed around the use of the platform.

It would be essential that the ODP community let its intentions and operational requirements be known quickly so as to orient the design of the platform in a most useful way.

CONCLUDING REMARKS

The alternate platform concept as presented here is of course only one of many options that could, and certainly will, be considered in future plans aimed at improving the efficiency of any drilling program. Other technical papers describe platforms and systems especially designed for deeper penetration into, and better recovery of, hard rock layers. The "station vessel" option presented here deliberately concentrates on a concept that can be realized immediately with state-of-the-art technology.

At this time the mode of operation of such a vessel within the framework of the ODP program remains to be explored ; it is clear that if the goals described above are to be met flexibility seems to be a prerequisite. Flexibility in the funding as well as in the planning of operations must be carefully examined. It does not appear feasible, or even desirable, to consider a joint financial support coming from the entire ODP community for the construction of the vessel. As far as operations are concerned a number of models can and will be considered. There is no doubt however that planning and scientific guidance will benefit greatly from coordination of activities within the JOIDES community.

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POSTSCRIPT

Ocean Drilling - Ready to Leap and Strike

LOOKING BACK

Dealing with ocean drilling is dealing with a project important not only for Earth Sciences but for Science History, too. As everybody knows, Deep Sea Drilling has been able to prove fundamental ideas and hypotheses based on geophysical methods such as continuous reflection seismics or paleomagnetism. These ideas were born in the free air and cultivated aboard many research vessels. But only by drilling down to rocks underneath the sea floor have we all obtained hard facts from geological, petrological, geochemical, paleontological and other investigations. To make out the evolution of the lithosphere is a historical enterprise as was Charles Darwin's approach to the evolution of the biosphere, a century ago. The project is a historical one in another respect, because it pioneered the idea that in Earth Sciences breakthroughs sometimes can come only by a "Big Science" approach. Now this idea is transgressing onto the continents, with continuous reflection seismic lines and scientific deep crustal drilling.

It is well known that the Deep Sea Drilling Project was launched in 1968 initially as a US endeavour and moved into the International Phase of Ocean Drilling (IPOD) in 1975 with five formal non-US members: Federal Republic of Germany, France, Japan, Union of Socialist Soviet Republics, and United Kingdom. It ended in 1983. Since 1985, it has been succeeded by the Ocean Drilling Program (ODP), based on the bigger drillship *JOIDES Resolution*, offering greater capabilities, able to accommodate bigger scientific parties and to tackle objectives thus far beyond reach, such as drilling deeper and in high latitudes. These objectives were identified at the first Conference on Scientific Ocean Drilling (COSOD) held in Austin, Texas in November 1981. This Conference was prepared and accompanied by several reports both from directly engaged scientists and from independent groups.

Continuously new ideas, findings and methods ask for rethinking and we all are happy that many new problems and discoveries were not foreseen by these groups. Hopefully this will also be the case for COSOD II, which tried to assess the ODP achievements up until now and to redefine scientific and technological objectives for the program's second half-life.

LOOKING AHEAD

Past success alone does not justify continuation, and a linear extrapolation of our present activities would neither match these successes nor justify the second COSOD's demand for involvement of more scientists, for new methods and instruments, and for more funds.

As a participant in many discussion and planning groups in geology and oceanography and also as a former active marine geologist aboard *Glomar Challenger*, I am deeply impressed by the spirit and outcome of the Conference which was held in Strasbourg in July 1987.

1) Generally the stress was directed towards attempting to better understand *processes* rather than to collect rocks and fossils and to decipher structures only. Of course this has to be done first in the future, too. At COSOD II dynamic questions were put forward, such as: How are fluids circulating through the earth's crust ? And what are the consequences of the transport of heat, gases, ions for the geochemical budget of the oceanic crust, the continental margins and the ocean itself ? Are these fluids really the *blood* of our earth ? And how to investigate the *pulse* of the solid earth ? What are the causes of possible different rates of sea floor spreading that influence sea level variations and earthquakes ? Why not measure the forces behind these phenomena directly ? How to understand climatic variations as cyclic processes, in order to be able eventually to forecast future changes ? Globally ? Even regionally ? And there are the many open questions about the biological evolution as a process embedded in the dynamic system atmosphere/hydrosphere/lithosphere : more or less linear versus non-linear evolutions, triggered by global or regional catastrophes ? May we even attack the problem of the origin of species as unique or as simultaneous events ?

2) These questions require new strategies such as global arrays of holes and more information from high latitudes for a better understanding of the paleoenvironment, or more undisturbed sediment cores from key areas with the most exactly defined thin time slices.

The other side of the coin is to drill deeper into sediments and into ocean crust, eventually down to the Moho, the real origin of the idea of deep sea drilling. *"On retourne toujours à ses premières amours"*. Cretaceous and Jurassic, or even Triassic, high sedimentation rate areas, deep oceanic crust, are well known keywords in these deep respects. And the strategy of patient and, at first sight, expensive key site drilling, as opposed to hasty drilling in every corner of our globe including political ones, followed by sometimes hasty publication, will certainly remain a matter of many controversial discussions - as we have had and continue to have aboard.

The most exciting new strategy, however, is the use of many more new and old drill holes as laboratories to measure geophysical and geochemical parameters, even continuously if a problem so demands. Indeed we need crust labs - both in the oceans and on the continents - parallel to space labs to better understand our whole earth.

3) To lay stress on processes requires more *multidisciplinary cooperation*. But from its beginning the

project was an international university, where everybody was a student to learn from others either in committees or aboard the drillship, now with even more space and opportunities to do so.

But again, we should not exclusively look downward aboard our ships, but landward, too. There are many questions of mutual interest and active geoscientists with century-long traditions and experiences. Therefore we should improve the *bridge from the deep ocean to the shelf and to the continent.* We should try to learn from our land colleagues not only about ophiolites but about their global plans of geotraverses to be complemented by offshore drilling. Of course we have in mind terranes and their possible candidates offshore. But ongoing discussions of transgressions and regressions are also part of the bridge, as are discussions of global or regional events to improve a stratigraphy for deep and shelf seas and continental areas, and discussions to improve our knowledge about the origin of stratification.

4) Looking ahead towards *new technologies*, the most important conclusion is the need for additional drilling platforms in order to make better use of *JOIDES Resolution* and to obtain global arrays of holes. Improving different downhole logging methods and the installation of the mentioned crust labs are multidisciplinary challenges, too.

LOOKING ASIDE

Most of these aims need *international cooperation*, and as President of the European Science Foundation I would like to repeat that one of the highlights of my whole geological career was to sign the contract between the National Science Foundation and the ESF in 1986. Through this signing, newcomers - and partly old-timers - from twelve Consortium members (Belgium, Denmark, Finland, Greece, Iceland, Italy, the Netherlands, Norway, Spain, Sweden, Switzerland and Turkey) became able to participate actively beside the "traditional" European members - Federal Republic of Germany, France and United Kingdom - and our colleagues from Canada, Japan and the United States.

Hopefully this will be the beginning of a marked increase in cooperation in all the scientific fields involved. This of course should not be meant as a start towards an inward-looking Europe opposed to the rest of the world but, on the contrary, towards a community making the best with little money and striving to be a good partner to the ultimate benefit of all partners.

Unfortunately at the moment there are some gaps in this international teamwork. One of the prerequisites of the historical success of this project, as I see it, is the stress on the participation of active scientists in planning, performing and publishing, with the help of non-governmental organisations. Of course these must have their governments' confidence because we depend largely on governmental money.

Therefore I hope that the recommendations of COSOD II may give a positive impression to all funding and even all cutting experts, governmental or non-governmental alike. The COSOD II proposals offer another chance for historical progress, for a qualitative leap towards a better understanding of how our Earth was and is working and therefore, ultimately, how it will work in the future.

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