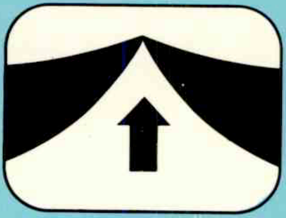
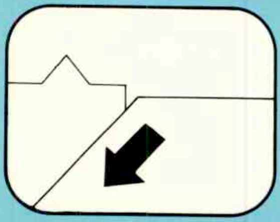
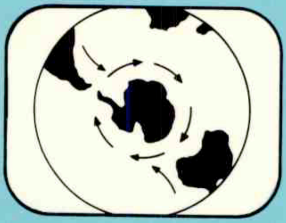
Report of the

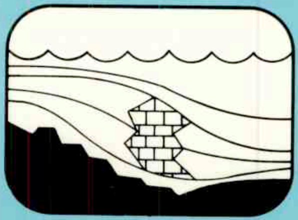
CONFERENCE ON SCIENTIFIC OCEAN DRILLING

November 16-18, 1981









Sponsored by the Joint
Oceanographic Institutions
for Deep Earth Sampling (JOIDES)

Report of the

CONFERENCE ON SCIENTIFIC OCEAN DRILLING

November 16-18, 1981

This document is based on a conference sponsored by JOIDES and held at the University of Texas at Austin on November 16-18, 1981 to discuss future scientific ocean drilling programs, problems, and objectives.

Additional copies can be obtained from:

JOI, Inc.
2100 Pennsylvania Ave., N.W.
Washington, D.C. 20037

The cover illustration is an adaptation from a recent textbook by James P. Kennett, MARINE GEOLOGY, © 1982, pp. 203, 319, 352, 695. Adapted by permission of Prentice-Hall, Inc., Englewood Cliffs, N.J.

TABLE OF CONTENTS

SUMMARY OF THE CONFERENCE ON SCIENTIFIC OCEAN DRILLING

WORKING GROUP POSITION PAPERS

ORIGIN AND EVOLUTION OF THE OCEANIC CRUST

TECTONIC EVOLUTION OF CONTINENTAL MARGINS AND OCEANIC CRUST

ORIGIN AND EVOLUTION OF MARINE SEDIMENTARY SEQUENCES

CAUSES OF LONG-TERM CHANGES IN THE ATMOSPHERE, OCEANS, CRYOSPHERE, BIOSPHERE, AND MAGNETIC FIELD

TOOLS, TECHNIQUES, AND ASSOCIATED STUDIES

PREFACE

The Conference on Scientific Ocean Drilling (COSOD) was initiated by the Executive Committee of JOIDES (Joint Oceanographic Institutions Deep Earth Sampling) who selected the steering committee and directed that the conference examine the question "how can ocean drilling and associated scientific programs be organized and coordinated to attack the most important scientific problems in the most organized and productive way?"

The COSOD Steering Committee met on May 21-22, 1981, and formed the following working groups:

I. Origin and Evolution of the Oceanic Crust
II. Tectonic Evolution of Continental Margins and Oceanic Crust
III. Origin and Evolution of Marine Sedimentary Sequences
IV. Causes of Long-term Changes in the Atmosphere, Oceans, Cryosphere, Biosphere, and Magnetic Field
V. Tools, Techniques, and Associated Studies

These groups subsequently met or corresponded to formulate position papers that served as the bases for discussion at the conference.

The Conference on Scientific Ocean Drilling was held at the Joe C. Thompson Conference Center at the University of Texas at Austin on November 16-18, 1981. In attendance were approximately 150 earth scientists including representatives from the United States, the Federal Republic of Germany, France, the Soviet Union, the United Kingdom, Australia, Canada, the Netherlands, and Norway.

The conference proceeded in the following manner. First, Allen Shinn, director of the Office of Scientific Ocean Drilling of the National Science Foundation, reviewed recent events related to scientific ocean drilling and what NSF considers to be the presently viable options for drilling platforms for the next decade. After this introduction, the chairmen of the COSOD working groups presented their groups' initial recommendations of scientific problems and goals for the next decade. Shorter presentations were then made by JOIDES panel chairmen and Ocean Margin Drilling Project (OMDP) working group chairmen of their committees' drilling program recommendations. Early on the second day of the conference, the general assembly broke down into individual COSOD working groups that included and encouraged discussions from conference attendees outside the committee structure of COSOD, JOIDES, and OMDP. While working groups 1-4 discussed scientific problems and priorities, working group 5 assembled information on the capabilities of a refitted *Glomar Challenger* and a converted *Glomar Explorer*. On the third (last) afternoon of the conference, the general assembly reconvened to hear and discuss the output from the working group meetings. The first four working group chairmen each presented a prioritized set of topics for scientific ocean drilling in the next decade based upon working group discussion of the initial position papers. The chairman of working group 5 then presented the contrasting characteristics and capabilities of a refitted *Glomar Challenger* and a converted *Glomar Explorer*. The question of the preferred vessel for future scientific ocean drilling was then examined in a open discussion of the general assembly moderated by the chairman of the COSOD steering committee. The result of this discussion is summarized as the first general recommendation of the steering committee.

The COSOD Steering Committee met on the day after the Conference to review the recommendations of the working groups and to organize the scientific and drill ship priorities into the written report which follows. The report consists of the following parts: introduction, general recommendations of the steering committee, top priority scientific recommendations, summary statement of the working groups, and the five working group position papers.

COSOD STEERING COMMITTEE AND WORKING GROUPS

STEERING COMMITTEE

Roger L. Larson, University of Rhode Island, *Chairman*
Jean Aubouin, Universite de Paris, FRANCE
James Baker, University of Washington
  Alternates: John Knauss, University of Rhode Island
    W.J. Merrell, Texas A&M University
Helmut Beiersdorf, Bundensanstalt fur Geowissenschaften und Rohstoffe, Hannover, FEDERAL REPUBLIC OF GERMANY
Robert Coleman, Stanford University
N. Terence Edgar, U.S. Geological Survey
R.M. Garrels, University of South Florida
H.R. Gould, Exxon Production Research Company
Christopher Harrison, University of Miami
J.D. Hays, Lamont-Doherty Geological Observatory
Kazuo Kobayashi, Ocean Research Institute, University of Tokyo, JAPAN
Drummond Matthews, Cambridge University, UNITED KINGDOM
  Alternates: J.R. Cann, University of Newcastle-upon-Tyne, U.K.
    Robert White, Cambridge University, U.K.
John C. Maxwell, University of Texas at Austin
Yuri Neprochnov, USSR Academy of Sciences, USSR

WORKING GROUPS

ORIGIN AND EVOLUTION OF THE OCEANIC CRUST

Jean Francheteau, Centre Oceanologique de Bretagne, FRANCE, *Chairman*
Rodey Batiza, Washington University
John I. Ewing, Woods Hole Oceanographic Institution
  Alternate: G.M. Purdy, Woods Hole Oceanographic Institution
Leonid V. Dmitriev, USSR Academy of Sciences, USSR
Michael J. Mottl, Woods Hole Oceanographic Institution
Paul Robinson, Dalhousie University, CANADA

TECTONIC EVOLUTION OF CONTINENTAL MARGINS AND OCEANIC CRUST

Anthony B. Watts, Lamont-Doherty Geological Observatory, *Chairman*
Rene Blanchet, Universite de Bretagne Occidentale, FRANCE
Robert S. Detrick, University of Rhode Island
Yuri Dmitriev, USSR Academy of Sciences, USSR
Charlotte E. Keen, Dalhousie University, CANADA
Seiya Uyeda, Earthquake Research Institute, University of Tokyo, JAPAN
  Additional Contributors: Eli A. Silver, University of California, Santa Cruz
    Kim Klitgord, U.S. Geological Survey

ORIGIN AND EVOLUTION OF MARINE SEDIMENTARY SEQUENCES

Wolfgang Schlager, University of Miami, *Chairman*
Michael A. Arthur, University of South Carolina
A.P. Lisitsyn, USSR Academy of Sciences, USSR
Frank Manheim, U.S. Geological Survey
Bernard Tissot, Institut Francais du Petrole, FRANCE
Brian E. Tucholke, Woods Hole Oceanographic Institution

CAUSES OF LONG-TERM CHANGES IN THE ATMOSPHERE, OCEANS, CRYOSPHERE, BIOSPHERE, AND MAGNETIC FIELD

Nicholas J. Shackleton, Cambridge University, UNITED KINGDOM, *Chairman*
Niles Eldredge, Museum of Natural History
Dennis V. Kent, Lamont-Doherty Geological Observatory
V.A. Krasheninnikov, USSR Academy of Sciences, USSR
T.C. Moore, Exxon Production Research Company
Hans R. Thierstein, Scripps Institution of Oceanography
Additional Contributors: Robert G. Douglas, University of Southern California
  B.R.T. Simoneit, Oregon State University
  Robert N. Ginsburg, University of Miami
  Ian G. Macintyre, Smithsonian Institute
  Eugene A. Shinn, University of Miami

TOOLS, TECHNIQUES, AND ASSOCIATED STUDIES

Timothy J.G. Francis, Institute of Oceanographic Sciences, UNITED KINGDOM, *Chairman*
Roger N. Anderson, Lamont-Doherty Geological Observatory
J. Dercourt, Universite Pierre et Marie Curie, FRANCE
Karl Hinz, Bundensanstalt fur Geowissenschaften und Rohstoffe, Hannover, FEDERAL REPUBLIC OF GERMANY
Claude Hocott, Gulf University Research Consortium
Carl H. Savit, Western Geophysical Company of America

SUMMARY OF THE CONFERENCE ON SCIENTIFIC OCEAN DRILLING

A. INTRODUCTION

The drilling of sediments and rocks of the ocean basins makes contributions to many branches of science. The continuous and detailed record of microfossils preserved in ocean sediments may give the best data for describing evolutionary changes and for understanding their causes. Sediments bear the imprint of ocean temperatures and currents, information critical to the reconstruction of oceanic circulation of the past and hence to the reconstruction of ancient climates. Drilling provides access to the rocks of the oceanic crust and thus helps to unravel their structures and motions, information required to understand the phenomena of sea-floor spreading and continental drift and, more broadly, the structure of the earth as a planet. Deep-sea sediments record the contributions of the rivers and winds of the past and thus the history of the continents, records otherwise lost by erosion of the land. In addition to greatly increasing our knowledge of earth history in general, the scientific information gained by drilling is basic to the search for mineral and petroleum resources both on land and beneath the seas. As the ocean is the last frontier for these resources, the importance of a thorough understanding of its geologic history and framework cannot be overstated.

Before the *Glomar Challenger* ever set sail on her initial trials, JOIDES identified as primary objectives for the Deep Sea Drilling Program "the determination of the age and processes of development of the ocean basins." Implicit in these objectives was the need to have long cores for "biostratigraphy, physical stratigraphy, paleomagnetism. . . and for studies of the physical and chemical aspects of sediment dispersal, deposition, and the post-depositional changes in sediments." The success of the program in achieving or progressing toward these goals is almost legendary. Indeed the results confirmed the concept of sea-floor spreading, the relationship of crustal age to magnetic anomalies, the basaltic nature of the oceanic crustal rocks, and, through the systematic sampling afforded by the drill, initiated an entirely new field of study — paleoceanography.

This technology has taken the science through more than a decade of unprecedented advancement and has been instrumental in bringing us to our present level of understanding of the origin and history of the ocean environment. That understanding stems primarily from reconnaissance drilling based on reconnaissance geophysical studies. We now need to advance our level of technical expertise in both drilling and geophysical surveying, as well as in downhole instrumentation. It is clear from the discussion and position papers presented at the Conference on Scientific Ocean Drilling that we are entering into a new era of ocean exploration utilizing the concepts of natural laboratories on the sea floor and carefully chosen arrays of drill sites to study general processes and global problems. In the past decade we have learned that the keys to geological processes and much of the history of the earth for the past 200 m.y. are recorded in the sediments and rocks of the ocean basins. We have only begun to read and to interpret the story that they hold.

B. GENERAL RECOMMENDATIONS OF THE STEERING COMMITTEE

1. A world-wide program of long-term drilling is an essential component of research in the earth sciences. The projects described here will require at least a decade to complete and will require drilling in the Atlantic, Pacific, Indian, and polar oceans. Many of these programs can be accomplished with the currently available drill ship *Glomar Challenger*, but the extended capabilities of the *Glomar Explorer* are required to accomplish a large number of other objectives. Thus, it is the unanimous conclusion of the conference attendees and the steering committee that *Glomar Explorer* is clearly the preferable vessel for future scientific ocean drilling. It is recognized that the availability of *Glomar Explorer* is subject to a yet-to-be conducted cost analysis and that the drilling system would almost certainly be operated without a riser and blowout prevention system for at least several years.
2. Future drilling must be part of a larger scientific program that includes adequate support for problem definition, site surveying, geophysical experimentation, and sample analyses. Broad-scale problem definition and fine-scale site examination and selection must precede drilling. The cores from the drill hole then become the ground truth that translates these geophysical parameters into geological reality. Lead times of two or three years are required for pre-drilling activities and support is required for post-drilling scientific analyses.
3. The integration of continental geology and marine geology should progress through scientific drilling programs. The oceans are the modern laboratories in which we can observe geologic processes typical of those that have occurred over the past 200 m.y. Understanding these processes is one of the keys to understanding ancient continental geology. We encourage this integration to proceed through the planning and execution of geophysical and drill-site transects from the dry land to the deep sea across well-chosen continental margins.
4. International cooperation should continue and expand. The *Glomar Challenger* program has cross-pollinated the scientific and cultural thinking of the earth science community in a fundamental and unique way. The resulting international research programs have been essential to the success of the program. Especially if the *Glomar Explorer* is utilized in the future, this international cooperation should be expanded. The JOIDES/IPOD (International Phase of Ocean Drilling) structure appears to be a good organizational framework for future drilling programs.

C. TOP PRIORITY SCIENTIFIC PROGRAM RECOMMENDATIONS

The following twelve scientific topics were selected by the working groups at COSOD as top priority objectives that should be attacked with scientific ocean drilling and related programs in the next decade. A further prioritization was not attempted by the steering committee, and these topics are listed here in a non-preferential order.

1. Processes of magma generation and crustal construction at mid-ocean ridges.
   What is the character and composition of the deep portion of the oceanic crust?
2. Configuration, chemistry, and dynamics of hydrothermal systems.
   What are the dimensions and characteristics of hydrothermal systems at ridge crests versus those on ridge flanks?
   How does overlying sediment cover, or the lack of it, affect these hydrothermal systems?
3. Early rifting history of passive continental margins.
   What is the shallow and deep structure of stretched and normal faulted margins versus those characterized by excessive volcanism?
4. Dynamics of forearc evolution.
   What are the relative motion, deformation, and pore water characteristics of sediments at accreting and erosional margins?
5. Structure and volcanic history of island arcs.
   What are the space and time relationships of forearc subduction, accretion, and erosion; and of backarc spreading, compression, and volcanism at island arcs?
6. Response of marine sedimentation to fluctuations in sea level.
   Which stratigraphic sequences and intervening unconformities represent fluctuations of sea level, and which represent vertical tectonic motion?
   What is the response of deep-sea sedimentation to fluctuations of sea level?
7. Sedimentation in oxygen-deficient oceans.
   What are the ocean circulation, paleoclimate, and potential hydrocarbon characteristics associated with black shale deposits?
8. Global mass balancing of sediments.
   What are the best estimates of the world sediment mass and composition balances in space and time?
9. History of ocean circulation.
   How do patterns of ocean circulation respond to changing ocean boundaries, e.g., changing ocean size, the extent of shallow continental seas, and the opening and closing of oceanic passages, especially the Drake passage, the Isthmus of Panama, and the Tethys seaway?
   What is the history of abyssal circulation?
10. Response of the atmosphere and oceans to variations of the planetary orbits.
    How do gravitational interactions with other planets, especially Jupiter, affect paleocirculation in the atmosphere and hydrosphere?
11. Patterns of evolution of microorganisms.
    How has the process of evolutionary change proceeded in marine organisms?
12. History of the earth's magnetic field.
    What is the nature of the magnetic field during a magnetic reversal?
    What is the detailed history of magnetic reversals and changes in the intensity of the magnetic field during the past 200 m.y.?

D. SUMMARY OF THE WORKING GROUP POSITION PAPERS

This summary statement is organized around the top-priority scientific recommendations listed above. The complete position papers of the working groups are printed in the following section. In this summary, recommendations duplicated by two working groups have been condensed under one heading. Each topic is numbered in the same manner as in the previous list. *We again emphasize that this numerical listing is not an attempt to further prioritize these topics, and that they are discussed in non-preferential order.*

D.1 Origin and Evolution of the Oceanic Crust

Introduction. The oceanic crust is built from overlapping volcanic units measuring approximately a few kilometers by a kilometer. These are erupted at mid-ocean ridges from vertical fissures within the very narrow zone where plates spread apart. The volcanic heat brought up by this process drives vigorous systems of hot springs that emerge at temperatures of up to 350°C, carrying with them iron, copper, zinc, and hydrogen sulfides, which react to form surficial sulfide ore deposits at the axes of ocean-floor spreading. As the crust cools, this initially vigorous circulation is replaced by different, gentler systems that carry iron and manganese oxides to the sea floor. The circulation not only alters the ocean crust and produces hydrothermal deposits but also controls the composition of the world ocean by exchanging elements, such as magnesium, calcium, sulfur, and oxygen, between sea water and rocks.

The highest priority proposals for drilling oceanic crust center on the concept of natural laboratories. These are arrays, or clusters, of holes, some deep, some relatively shallow, grouped together in fours and fives in particularly critical parts of the ocean floor. Not only would samples be extracted from the holes, but they would be used for emplacement of sophisticated instruments, some during the drilling period, and others for long-term monitoring after drilling had ceased. The group of holes in any such cluster would be spaced closely together, often no more than a few hundred meters apart, to facilitate the conduction of experiments and collection of samples on the same scale as that of the architecture of the oceanic crust.

1. Processes of Magma Generation and Crustal Construction at Mid-Ocean Ridges. Within each laboratory complex, one hole would be targeted for deep penetration to allow sampling material from hitherto unreached levels in the ocean crust. Developments in drilling techniques and in vessel capability have at last put such targets within our grasp and open the possibility of sampling the layers of the crust as yet characterized only indirectly by geophysical studies. Such information would allow both the calibration of the great resource of existing geophysical data and the extension of drilling results laterally by geophysical means.

2. Configuration, Chemistry and Dynamics of Hydrothermal Systems. Some of the natural laboratories would be chosen primarily to study hydrothermal circulation, investigating inflow and outflow areas, collecting both rocks and fluids from the holes, and measuring temperature, fluid flow rates, and in-hole chemistry of flowing water. Initially, laboratories would be set up in more technically accessible areas, such as active, medium-temperature systems and extinct, high-temperature systems, using techniques which are now available. Eventually, however, two of these would be placed in zero-age crust, one in the fast-spreading crust of the Pacific and the other in the slow-spreading Atlantic crust, using special new engineering facilities for starting holes on bare-rock surfaces. Other laboratories would be chosen to examine the way the crust is constructed, monitoring the chemical characteristics of the lavas and using the signature of the earth's magnetic field, which was frozen into the lavas when they were formed, to act as a marker within the volcanic pile.

Other Important Problems. Drilling has provided important insights into mantle processes, hot spots, heterogeneity, and generation of flood basalts. Many targets of this kind remain to be drilled, especially within the Pacific, and clearly would have great scientific merit. Aging of the oceanic crust leads to changes in crustal structure and interchange of elements between ocean water and crustal rocks. Drilling is the only way to study this effectively. Geophysical work on the large transform faults that offset the mid-ocean ridges suggests models of processes within these important structural elements of the ocean crust. Drilling will clearly be important in testing such models. Young ocean basins, such as the Gulf of California, give insights into processes of crustal splitting and the development of new continental margins. They are also sites of intense high-temperature hydrothermal activity and of complex volcanism. Metamorphism and mineralization occurring in thick sediments in one or more young oceans should be investigated by drilling.

Finally, the region of the island arcs that fringe the Pacific are important elements in the oceanic crustal story. They are zones where characteristic ore deposits are developed and where a variety of very different volcanic magmas are available. Such zones have been incorporated into continental crust, and drilling into regions of active island arcs to understand processes there will not only benefit marine geology but will have great importance for understanding the development of continents.

D.2 Tectonic Evolution of Continental Margins and Oceanic Crust

Introduction. The concept of plate tectonics holds that the outer shell of the earth is broken into a few large plates that move relative to each other. This outer shell, known as the lithosphere, is about 100 km thick and is rigid except at the boundaries of the plates. Plate tectonics can be fairly called a revolution in the earth sciences because most earth scientists now accept the evidence for large scale horizontal motion of the lithosphere. This motion, originally called continental drift, has been quantified by marine geophysical studies in recent years so that the amounts, rates, and directions of past and present horizontal motions are precisely known for most regions.

Plate boundaries occur where two plates are diverging, converging, or slipping past each other. In the oceanic realm, plates diverge at mid-ocean ridges, where new lithosphere is formed from hot, upwelling magma. Evidence for the initiation of this divergence is preserved at the passive margins of the diverging continents. Plate convergence in the oceans takes place at active margins, where one plate is subducted beneath another. These plate boundaries are the focus of major tectonic questions that can be solved with programs of scientific ocean drilling. At divergent boundaries, the major question is the nature of breakup of continents prior to sea-floor spreading. At convergent boundaries, the focus is on island arcs, their structure and volcanic history. These volcanic islands, arrayed in a curved, or arcuate pattern, are the dry-land expression of a complex tectonic system. On the oceanic, or forearc, side of the islands lie the deep-sea trench and other compressional structures associated with subduction of the oceanic lithosphere. On the continental, or backarc, side of the islands lie the backarc basins generally believed to form by crustal extension.

3. Early Rifting History of Passive Continental Margins. Two major types of passive margins have been identified. In one there is a significant amount of continental crustal stretching resulting in normal faults. In the other, the early breakup is marked by massive outpourings of volcanic material, resulting in seaward dipping seismic reflectors. The objective of drilling is to study the deep structure of both types of margins, including the nature and extent of stretched continental crust, the nature of the seaward dipping reflectors, and the relative proportion of pre-rift sediments deposited during rifting. This can be accomplished by drilling transects across sediment-starved margins such as the Bay of Biscaye, northwest or southwest Australia, the Lord Howe Rise, and the Grand Bahamas (normal faulted margins), and Norway, Argentina, Southwest Africa, Greenland, or Antarctica (seaward dipping reflectors).

4. Dynamics of Forearc Evolution. The evidence that forearc basins can either accumulate sediments or be eroded through time needs to be evaluated by delineating the characteristics of the sediments in the forearc basin. In particular, the pressure, flow, and composition of fluids in the sediments, the vertical and lateral motions of sediments through time, and deformation stages along and across the sediments at depth need to be studied as functions of material input and convergence parameters. These phenomena should be studied in both erosional and accreting forearc regions; and comparisons should be made between ocean-continent margins and ocean-ocean margins. Examples of accreting margins are the Lesser Antilles, Oregon-Washington, the Aleutians, the Sunda Arc, and Ecuador, whereas non-accreting or erosional margins are found in Japan, Peru, Central America, and the Marianas.

5. Structure and Volcanic History of Island Arcs. The importance of timing of events across convergent margins is stressed in this type of study. The backarc basins are known to have spread at times, but occasional times of compression are also recognized. The volcanism of the island arc is also episodic, as is the dynamic history of the forearc basin. Transects which cross all portions of a convergent margin will help to determine the relative timing of all these episodic events.

Other Important Problems. In addition to the three top-priority topics listed above, the tectonics group identified top-priority crustal and sedimentary studies which are incorporated with topics 1, 2, and 6. Other important tectonic topics can be grouped into passive margin, active margin, and oceanic crust problems. Future drilling of passive margins should investigate the development of continental slopes and rises, the detailed history of vertical movements (both uplift and subsidence) at margins, thermal and mechanical evolution of passive margins, variability along strike in margin structure, sheared margins, and the nature and origin of post-rifting tectonic events on passive margins. Problems for drilling active margins include the study of stress fields at active margins, global relations between arc systems, collision tectonics, and the development of passive margins in backarc basins. Problems of oceanic crustal tectonics include the determination of plate kinematic models; determination of the magnetic reversal time scale, the crustal structure, and tectonic evolution of aseismic ridges and oceanic plateaus; the timing, extent, and origin of intraplate volcanism; the structure of transform faults and fracture zones; and the study of coral atolls and guyots and their volcanic cores.

D.3 Origin and Evolution of Marine Sedimentary Sequences

Introduction. Sedimentation in the oceans, and ultimately the stratigraphy of marine deposits, depends strongly on the changing depths and shapes of ocean basins that result from processes of plate tectonics. However, marine sedimentation also responds to, and records the variations in, oceanic and atmospheric circulation, biological productivity, continental elevation and runoff, world-wide sea level, and the climate of the planet. The most important questions focus on the global control of sedimentation by the interplay of tectonics, sea level, and climate. We shall depend strongly on ocean drilling in the future to describe the long-term history of this interplay by studying three topics that have particularly far-reaching implications: deep-sea sedimentation versus changes in sea level, sedimentation in oxygen-deficient oceans, and sediment mass balances.

6. Response of Marine Sedimentation to Fluctuations in Sea Level. It is hypothesized that the sequences of onlap and offlap and intervening unconformities observed in the seismic stratigraphy of continental margins often represent global fluctuations in sea level. The timing of these fluctuations can be calibrated with drill core data, although the magnitudes of changes of sea level are poorly known. The proposed curve of eustatic sea level has notable, abrupt regressions that occur at several times in the Cretaceous/Tertiary record. In order to test this hypothesis, drilling should be done in two types of settings. The first is in sediment-rich continental shelves in which seismic unconformities can be seen. This will enable us to identify the sedimentary causes and the timing of the seismic unconformities. It is necessary that good paleodepth control be available, which probably means that shelf areas such as the east coast of the United States are the prime target areas. It will also be advantageous to drill on carbonate banks and platforms, such as the Bahamas, or on atolls and guyots. There the carbonates are produced close to sea level so that the difficulty of knowing the paleowater depth is removed. Provided that good enough age control is available, it should be possible to see unconformities produced by proposed fluctuations of sea level. The large Oligocene fall in sea level and the smaller changes during the Mesozoic are of special importance.

Although it is widely accepted that fluctuations of sea level exert a strong control on shelf sedimentation, there is no consensus on how the deep sea responds to these changes, whether deep-circulation varies systematically with sea level, and whether unconformities on the shelves extend into the deep sea. Drilling on transects across seismically well-documented passive ocean margins (e.g., North Atlantic, Gulf of Mexico, western Australia) is needed to answer these questions.

7. Sedimentation in Oxygen-Deficient Oceans. Large volumes of organic-rich sediments were deposited during certain periods in earlier history, such as the Cretaceous and the Eocene, when sea level stood higher and climate was more equable than today. These deposits are both economically important and scientifically puzzling. We recommend a concerted effort to study the sedimentology and geochemistry of these deposits by drilling transects across some Cretaceous ocean basins (North and South Atlantic, equatorial Pacific) and by studying small-scale, modern analogs such as zones of upwelling off Peru, southwest Africa or southern Arabia.

8. Global Mass Balancing of Sediments. Mass balancing implies a global view of sedimentation and depends largely on ocean drilling for basic information on volumes and composition of sediments. Standardized analyses and continuously updated data banks can greatly improve the effect of ocean drilling in this field. Drilling also provides the only opportunity to obtain crucial information on specific areas that acted at certain times as local sinks of materials and had a disproportionately large effect on global mass balance. Examples include giant evaporite deposits in the South Atlantic, the Gulf of Mexico, and the Mediterranean.

Other Important Problems. A number of other problems are of general significance and depend largely on ocean drilling for their solution. These include the sedimentary record of abyssal circulation and its history in the Mesozoic and Cenozoic; the anatomy of gravity-displaced sediments, including both large-scale slumps on continental slopes and submarine fans; glacio-marine sediments as monitors of the waxing and waning of polar ice; carbonate platforms as indicators of changes in sea level, vertical tectonics, and surface conditions in the oceans; the sedimentary signature of specific tectonic domains, such as trenches, continental rises, and backarc basins; marine hydrology, i.e., the movement of pore water fluids and the resulting alteration of slowly compacting sediments, both on continental margins and under hydrothermal conditions over oceanic crust.

D.4 Causes of Long-Term Changes in the Atmosphere, Oceans, Cryosphere, Biosphere, and Magnetic Field

Introduction. There now exists an important opportunity to conduct an integrated study centered on the history of circulation of the ocean. Our present knowledge of ocean circulation and its important role in the climate system derives primarily from studies of the modern ocean and its interaction with the atmosphere. Studies of the Pleistocene ocean have added to our knowledge, but we have little understanding of ocean circulation in the more distant past. Insights into the sensitivity of the earth's climate to different oceanic circulatory states can be derived either from modeling these states or studying deep-sea sediments that give us past measures of specific characteristics of these states. Yet models ultimately need evidence from the geologic record to be substantiated.

Since the evolution of marine organisms took place within the changing circulatory regime of the ocean, insight into the evolutionary process can best be gained by studying evolutionary change concomitantly with studies of past oceanographic change.

We are now in a position to launch a global study of past ocean circulation and the simultaneous evolution of ocean biota for three reasons: (1) detailed studies of Pleistocene deep-sea sediment have provided the analytical techniques needed; (2) deep-ocean sediment sampling programs (both piston coring and drilling) have provided a knowledge of the global characteristics of deep-sea sediments so that the best sampling sites for such a project can be carefully selected; (3) the development of the hydraulic piston core has provided a means of acquiring sequences of undisturbed sediments from deep below the sea floor (200 meters).

We envisage an experimental design for a study of the circulation history of the ocean of the following form. A sampling program (after careful analysis of existing data and site-survey information) would be designed to produce a global array of horizontal and vertical transects of the world ocean. The vertical component would be achieved by sampling different depths in the oceans such as the flanks of oceanic ridges or continental slopes. Sufficient sites would be needed to monitor major water masses and boundaries of important water masses. This set of cores then would become a global monitoring system for studying the changing patterns of ocean circulation, biotic evolution, and behavior of the earth's magnetic field. The core array would allow monitoring of specific aspects of the hydrosphere, biosphere, and magnetosphere including the following.

9. Ocean Circulation History. How has ocean circulation responded to changing boundary conditions through time, such as changes in ocean size, alterations of important oceanic passageways (e.g., the Tethys Seaway), changing climatic conditions, and changes in the wind driven circulation? What was the structure and circulation pattern of the ocean when there was no permanent ice, and what was the relative importance of evaporation and cooling in the formation of deep water during these ice-free times?

10. Response of the Atmosphere and Oceans to Variations of the Planetary Orbits. The changing geometry of the earth's orbit around the sun appears to have controlled the timing of major Pleistocene climatic changes. Since these orbital changes are caused by gravitational interactions between the earth and the other planets, primarily Jupiter, they should extend into the distant past. The response of the earth's climate system to these changes, however, is dependent upon the configuration of the boundary conditions of the system at any given time. In order to learn more about the sensitivity of our climate to changes in these boundary conditions, we can measure the ocean response to orbital variations when the earth had no permanent ice, extensive shallow seas, and ocean basins of different size and shape. These measurements will be critical to those attempting to understand how our climate system works and to predict future climate.

11. Patterns of Evolution of Microorganisms. Deep-sea sediments provide the best geologic medium for studying evolutionary change. Such studies will be far more reliable if they are coupled with paleoceanographic studies. The global array of cores will allow the mapping of morphologic change in space and time, and the paleoceanographic studies will provide an opportunity to differentiate between morphologic change induced by changing ecologic conditions and morphologic change due to changing genetic structure. The rate of evolutionary change can be measured and the rate at which these changes are dispersed through the ocean by migration can be accurately mapped.

12. History of the Earth's Magnetic Field. It has been hypothesized that the main dipole field component of the earth's magnetic field breaks down during the reversal process, although very little information is available on the details of these transitions. In order to test the nature of the earth's field during reversals, it is necessary to recover high-sedimentation rate cores that are azimuthally oriented from both hemispheres and all oceans. If the quadrupole or octupole field components dominate during these transition intervals, the records from widely separated sites will be markedly different.

Although the obvious reversal sequences have been documented by studies of deep-sea cores and sequences of magnetic anomalies, there have been many reports, often poorly substantiated, of occasions during which the earth's magnetic field either reversed very briefly or went through a large intensity fluctuation and then emerged in the same orientation. The nature of the earth's magnetic field and the reversal process has been approached with statistical calculations that predict the frequency of occurrence of reversals. Testing such analyses is not possible until the nature of the short events is resolved because inserting even a few short period polarity events into a presently accepted reversal time scale would completely alter the frequency spectrum of that time series. The set of cores necessary for the study of the reversal process is also necessary here because the possibility exists that the short events are non-dipole phenomena. In addition, if care is taken to locate some of these cores downwind from sites of Tertiary and Cretaceous volcanism, it should be possible to establish a direct correlation of radiometric and reversal time scales by dating volcanic ash layers in the midst of the reversal sequences.

D.5 Tools, Techniques, and Associated Studies

Platforms. The *Glomar Challenger* has been an outstanding platform for conducting the drilling for the past 13 years and she is capable of continuing her role for an additional 5 to 10 more years. In the short term she may represent the most economical means of continuing the current program, but in the longer view the *Glomar Explorer*, owned by the United States government, may prove to be the better choice. This larger ship offers the following technical features believed to be most relevant:

1. The *Glomar Explorer* has a displacement six times greater than the *Glomar Challenger* and a draft that is almost double. These characteristics make it a very stable platform that would enable drilling operations to continue when on *Glomar Challenger* they would have to shut down.
2. Greatly increased laboratory and living facilities on the *Glomar Explorer* would permit an increased number of scientists to participate in the cruises, offering the possibility of expanding the membership in IPOD. In addition, there would be room to accommodate technicians needed for proposed downhole instrumentation programs and engineers for testing new devices to support a continuing program designed to improve the drilling and coring capabilities.
3. The *Glomar Explorer* can be ice-strengthened permitting transit in small block ice conditions to drilling sites in high latitudes, a modification not feasible on the *Glomar Challenger*.
4. A large mud capacity on the *Glomar Explorer* could be important if drilling without mud return proves viable and is essential if a mud return system is adopted.
5. A longer drill string will be available for use in deep-water targets, but use of this capability is dependent on drill-string design as well as smaller motion expected for the larger ship.

The size of the *Glomar Explorer* has the following disadvantages:

1. It cannot transit the Panama Canal.
2. The choice of ports and drydocking facilities is limited.

Both vessels would need a refit requiring the *Glomar Challenger* to be in drydock 1 to 2 months and the *Glomar Explorer* from 12 to 18 months.

Conclusions. The selection of the vessel will depend greatly on economic considerations not discussed here, but also the decision will bear heavily on the perception of the duration of scientific drilling in the ocean. Although *Glomar Explorer* will offer advantages even in the short term, economic considerations may dictate the use of the *Glomar Challenger*. If, on the other hand, drilling in the oceans is perceived to be an on-going program extending even beyond the 1980's then the balance falls in favor of the *Glomar Explorer*. Not only does the *Glomar Explorer* have the advantage of being a new vessel capable of at least 20 years service, it also has appreciable growth potential in capability. The use of full riser and mud systems, large storage capacity, capability for deployment of heavy equipment, and the housing of engineers and technicians on the ship all become feasible.

The COSOD general assembly unanimously endorsed the use of the *Glomar Explorer* as the preferred vessel to achieve the scientific goals described in this report.

Drilling Technology. There must be a continuing effort to improve our capability to drill deeper into both sediments and rock and to recover a greater percentage of the rock cores while maintaining or improving the quality of the condition of the sample retrieved. This may require a broader application of conventional techniques, such as the use of mud, casing, and, in hard fractured rock, grouting, and a commitment to advancing the technology. Better heave compensation coupled with downhole sensors could greatly enhance penetration and core recovery by maintaining closer control on bit dynamics or facilitating the use of downhole motors or turbo-drills that are sensitive to bit pressure. Coring devices that extend into the sediment ahead of the bit may be modified to cut cores from hard rock.

Currently there is no capability to drill directly into basalts on the sea floor without a sediment cover to stabilize the bit. A system that would enable drilling in areas without sediment cover is feasible and will greatly extend the value of deep-ocean drilling by providing the first opportunity for scientists to probe the system of circulation of hot water and mineral deposition actively taking place.

Logging and Downhole Experiments. A detailed report has been prepared on the use of logging in the deep oceans to enhance the scientific return from a drilled hole. Newly developed techniques will provide for the long-term emplacement of instruments in a hole abandoned by the drill ship by using conventional oceanographic vessels or perhaps even by deep submersibles.

Geophysical and Geological Studies. The COSOD scientific working groups have designed programs that emphasize the solving of geologic problems rather than continuing the quest for reconnaissance information. This new direction requires, more than ever, extensive regional and site-specific surveying and study prior to drilling. Such activities require long lead times and better long-term planning, both for the surveys and the drilling. Long-term planning requires a commitment by funding organizations to a continuing program of drilling beyond the relatively short funding period.

Many new instruments designed for surveys of large and small scale have been developed recently and undoubtedly more will be forthcoming. Scanning sonars, real-time swath mapping of sea-floor features, cameras capable of photographing large areas of the sea floor, sea-floor seismic systems, and submersibles are all available for deployment where required.

ORIGIN AND EVOLUTION OF THE OCEANIC CRUST

A. INTRODUCTION

The scientists selected by COSOD Steering Committee (J. Francheteau, chairman, R. Batiza, L. Dmitriev, J. Ewing, M. Mottl, M. Purdy, and P. Robinson) met (except L. Dmitriev and P. Robinson who were unable to attend) at Woods Hole Oceanographic Institution on 3-4 September, 1981. The working group had as a task to examine the question "How can ocean drilling and associated scientific programs be organized and coordinated to attack the most important scientific problems in the most orderly and productive way?". Working Group 1 on "Origin and Evolution of the Ocean Crust" was to specifically address the question of how the problems of the oceanic crust may or may not be elucidated by ocean drilling. WG 1 reviewed a number of pertinent documents including the Ocean Crust Panel white paper, a paper prepared for our meeting by the USSR Working Group on Deep Sea Drilling, and a tentative proposal for future drilling drafted for the JOIDES Planning Committee. WG 1 has identified high priorities for drilling into the oceanic crust, with a strong focus on processes, in order to contribute to solving major oceanic crustal problems. WG 1 is also issuing recommendations for a drilling program. The first draft of the WG 1 report was modified to incorporate contributions from scientists attending the COSOD Austin Conference (16-18 November, 1981) (T. Atwater, J. Cann, L. Dmitriev, M. Flower, R. Kidd, J. Kirkpatrick, K. Klitgord, J. Malpas, J. Maxwell, J. Natland, J. Phillips, P. Robinson, H. Schmincke, J. Tarney) and others (T. Crough, D. Karig, J. Morgan, J.-G. Schilling).

The task of WG 1 is somewhat facilitated because we have at our disposal a reasonably precise conceptual model of the oceanic crust formation. Although the topics discussed below are, therefore, not new we feel we present a novel approach.

First we emphasize the concept of natural laboratories: an array or cluster of holes grouped in critical parts of the ocean floor. The drilling tool is unexcelled here in two fundamental ways: firstly, it provides access to the otherwise unreachable interior of the crust in order to conduct in situ measurements, and secondly, it enables the recovery, from within the crust, of material which can then be subjected to extensive laboratory analyses and measurements. These two qualities of the drilling tool take their full value when drilling is conducted in regions where processes are active.

Second we view drilling as being part of a much larger experiment conducted within the natural laboratory. A lot of remote geophysics and geology must be achieved before drilling, and the long-term use of the drill site should be insured.

B. MAJOR PROBLEMS OF THE OCEANIC CRUST THAT WE RECOMMEND BE INVESTIGATED BY DRILLING

We recognize two high-priority problems to be investigated by drilling into the ocean crust that are clearly outstanding in their significance. These are (1) the processes of magma generation and crustal construction operating at mid-ocean ridges and (2) the processes of hydrothermal circulation in the crust. We also recognize several important problems that are worthy of investigation. These are (1) compositional heterogeneity of the mantle and mantle evolution, (2) aging and evolution of the crust, (3) formation of overly thick crust, (4) the role of transform faults, (5) processes operating in young ocean basins, and (6) island arcs and backarc basins. Some of these lower-priority objectives can be investigated in the context of a drilling program designed to examine the high-priority problems.

B.1 High-Priority Objectives

Two-thirds of the Earth's crust is formed at mid-ocean ridges. In order to understand the processes of origin of this segment of the crust we recommend continued investigation by drilling. Such drilling should be used to investigate active processes of crustal construction and subsequent evolution.

Processes of construction begin with primary magma generation in the mantle. These magmas then rise and coalesce into pockets forming bodies of variable shapes and dimensions at shallow levels beneath the ridge axis. The magmas undergo processes of mixing and differentiation prior to eruption or crystallization in situ. The eruptive lavas are recognized as the upper portion of the oceanic crust. The in situ products of crystallization are believed to comprise the lower part of the oceanic crust. These upper and lower portions of the crust are separated by a transition region possibly represented by sheeted dykes on the basis of ophiolite analogies. A major source of our information is in ophiolite complexes which are thought to be slabs of representative oceanic crust tectonically emplaced onto continents. We infer a generalized model of oceanic crustal structure that consists of a 1-km-thick extrusive basalt carapace that grades into a 1-km-thick complex of sheeted dikes characterized by minerals of pervasive greenschist and amphibole facies which in turn is underlain by a 2- to 5-km-thick plutonic section. The topmost section of the plutonic unit consists of unlayered gabbro and trondheimite, is extremely heterogeneous, and displays complex metamorphic relationships. At deeper levels cumulate gabbros exist that in turn grade into cumulate ultramafics.

The seismic structure is perhaps the most well-determined characteristic of oceanic crust and, indeed, constitutes its only unambiguous definition. Seismically, oceanic crust may be divided into two distinct zones which traditionally have been called Layer 2 and Layer 3. The former is characterized by compressional wave velocities between 2.5 and 6.5 km/sec and steep vertical velocity gradients of 1-4/sec. Layer 3 is characterized by very small velocity gradients (0.1/sec) and velocities in the range 6.7-7.0 km/sec. The Layer 2/3 boundary typically occurs 1.5-2.5 km beneath the sea floor.

Cooling of the oceanic crust is accomplished rapidly by circulation of sea-water in hydrothermal systems, leading to changes in the physical and chemical nature of the crust, formation of ore deposits on the sea floor, and modification of the chemical composition of the world ocean.

It is obvious that this generalized model must be tested by drilling, and also that through drilling one should be able to assess the properties of the principal active processes of magma generation, crustal construction, and hydrothermal circulation.

Processes of Magma Generation and Crustal Construction Operating at Mid-Ocean Ridges. Drilling into the ocean crust so far has elucidated the structure and composition of only the uppermost 100 to 600 meters of the Atlantic- and Pacific-type crust. The next task for drilling is to study the lower two thirds of seismic Layer 2, the nature of the Layer 2/3 transition, and the upper portion of Layer 3. More than two thirds of an average oceanic crustal column is Layer 3-type material, and yet we do not know the nature of this material. The Layer 2/3 boundary is the only identifiable boundary within oceanic crust. It has been recognized in all the world's oceans, and yet we do not know the nature or origin of this boundary. We cannot unambiguously relate these globally determined seismic characteristics to our inferred geological sections. These are not only fundamental gaps in our knowledge, but they make it impossible to formulate credible models for crustal accretion. Because we have no direct sampling of the deep crust, we cannot confirm the validity of the ophiolite analogy and thus confidently apply the wealth of knowledge available from this source to our understanding of the formation and evolution of oceanic crust. Because we have no direct sampling of the deep crust, we cannot relate seismic velocity determinations to physical properties or composition, and, in consequence, we waste a huge resource of presently available information and make future seismic experiments of significantly less value.

The nature of the Layer 2/3 transition is unclear and several hypotheses of its origin have been proposed. Does the boundary represent the greatest depth to which small-scale cracking of the ocean crust extends? Is the interval a lithological boundary between intrusive basalt and gabbro, or between basalt and serpentinized mantle? Is the discontinuity a metamorphic boundary between greenschist and amphibolite facies, or between low- and high-greenschist facies? Thus drilling will provide a critical test of the ophiolite model and will provide the ground-truth calibration of seismic structure.

Crustal construction is achieved by extrusive, intrusive, and tectonic processes. In order to understand the processes by which the extrusive layer is formed, we need to know the spacing, periodicity, and volume of submarine eruptions. This information can be gained by determining the thickness and lateral extent of lithologic units in the crust, the eruptive chronology, and the extent of interfingering of separate volcanoes. Submersible studies and drilling of the upper part of Layer 2 suggest that most eruptions occur along fissures in the axial zone of the mid-ocean ridge, building up edifices several hundred meters long and fifty to two hundred meters high. On the basis of magnetic and geochemical data, eruptive activity appears to be episodic. In addition, the locus of eruptive activity probably fluctuates with time.

It is not clear how the magmas migrate from chambers beneath the sea floor to the sea floor. Does "steady-state" spreading produce a continuously opening fracture system through which the magma moves, leading to a sheeted dike complex? Or are the magmas emplaced laterally from point sources in a process analogous to that observed in Iceland? The answers to such questions will have a major bearing on the structure of the upper crust, the pattern of hydrothermal circulation and also the origin of magnetic anomalies.

The tectonic processes that give rise to the structural complexity of the oceanic crust are closely related to the magmatic processes occurring at the ridges. Previous drilling has shown that the upper levels of the crust, at least in slow-spreading ridges, consist of faulted and tilted blocks. A major remaining question is whether this complex structure is due to extrusion of lava as subsidence proceeds in the axial zone of the ridge, to mass wasting on the margins of the rift valley, or to faulting during migration of the newly-formed crust out of the axial zone. Another major question is whether this structural complexity continues into the lower levels of Layer 2 and Layer 3.

The geometry of crustal emplacement and the origin of magnetic anomalies are closely linked and can be determined from drilling magnetic reversals in Layer 2 and in the upper part of Layer 3. Elucidation of the sources of the magnetic anomalies is essential for confirming the Vine-Matthews hypothesis and for improvement in the identification and dating of magnetic anomalies. This requires determination of the intensity of magnetization and the shapes of the causative bodies in the oceanic crust. Boundaries of magnetic reversals must generally dip toward the ridge axis in the volcanics, become steep in any layer of sheeted dykes, and dip gently away from the ridge axis in the gabbro. The exact shape of these boundaries is a function of the geometry of crustal accretion and can be "inverted" to give much information on the latter process.

From closely spaced holes through the same reversal boundary in the upper part of Layer 2 it should be possible to separate variations in paleomagnetic inclination caused by tectonic rotations from those caused by behavior of the magnetic field. From the amount of tectonic rotation, the shape of the reversal boundary, and the variation in extent and thickness of volcanic units between holes, it is possible to determine (1) the width of the extrusive zone at the ridge axis, (2) the spatial and temporal distribution of volcanics erupted within this zone, and (3) the amount and distribution of down-faulting involved in forming the volcanic layer. The whole process, and particularly the latter, is critical to understanding the active hydrothermal circulation at the ridge axis and the formation of massive sulphides.

In Layer 3, boundaries of magnetic reversals will correspond to the 580°C (Curie point of magnetite) paleo-isotherms. The shapes of these, with outward slope roughly inversely proportional to spreading rate, will give some measure of the size of magma chambers and the degree of hydrothermal penetration of Layer 3 at the ridge axis.

Thus combined with direct information, such as the increase in the number of dykes with depth in Layer 2, drilling of carefully positioned, closely spaced holes on a magnetic reversal boundary will give valuable insight into the origin of the magnetic anomalies and the process of crustal accretion. Unless reliable methods of orienting drill cores are developed to give azimuth directions, sites should be selected in as high a latitude as is logistically reasonable. Initially this should be carried out on a non-rifted ridge where the tectonic complexities are much less than on rifted ridges.

Formation of the intrusive layer in the lower part of the crust depends largely on the nature of magma chambers beneath the sea floor. Are the systems of magma supply large, steady-state chambers in which new magma is continuously being mixed with evolved magmas, or are they a series of smaller, independent chambers undergoing separate evolutions? Studies of basalt geochemistry in the North Atlantic Ocean suggest that, at least at slow spreading ridges, steady-state magma chambers are unlikely. At fast-spreading ridges, magma chambers may be larger and longer lived. The size and spacing of the chambers will have a major influence on the pattern of hydrothermal circulation beneath the spreading axis and will control the structure of the lower parts of the crust. Drilling into the intrusive layer will allow us to examine the size, shape, and lateral extent of fossil magma chambers and relate these to the extrusive layer.

In summary, a coherent drilling strategy in Layer 2 and possibly Layer 3 will provide key evidence for elucidating processes of magma generation and crustal construction operating at mid-ocean ridges. Specifically, it will provide a test of the ophiolite model, calibrate the seismic structure, and shed light on the volcano-tectonic processes, including processes taking place in magma chambers. It will also bring constraints on crustal emplacement and paleoisotherms through a reversal drilling experiment. Finally, it will provide important evidence on the formation of the lower oceanic crust which is directly linked to dynamics of magma chambers.

Configuration, Chemistry and Dynamics of Hydrothermal Systems. Convectively-driven, seawater-fed hydrothermal systems within the oceanic crust are believed to have a major impact on (1) heat loss from newly formed lithosphere; (2) crustal formation and aging, including changes in chemistry, mineralogy, and physical properties; (3) geochemical mass balances; and (4) formation of ore deposits on and within the crust. These hydrothermal systems can be divided into two types based on the major source of the heat they are tapping.

"Active" systems tap mainly the "high-grade" magmatic heat associated with the crystallization and initial cooling of the basaltic crust. As a result they produce high-temperature waters, such as the 350°C solutions which exit the sea floor or mix in the shallow subsurface on the East Pacific Rise at 21°N and the Galapagos Rift at 86°W. Active systems are probably restricted to very young crust in the axial region and are intimately related in some way to volcanic processes. Their solutions are rich enough in metals and sulfur to form ore-grade massive sulfide deposits on and within the crust.

"Passive" systems, by contrast, occur on older crust and tap only heat which is conducted across the Moho from the cooling mantle. The circulating waters in these systems are much cooler. Evidence from studies of heat flow indicates that this type of circulation can remove heat from crust up to tens of millions of years in age. Even after old crust becomes sealed to further advective heat loss, passive systems can persist beneath the sediment blanket.

Because of the different duration, heat source, and resultant temperatures in these two types of systems, the alteration which occurs differs greatly with respect to both chemical and mineralogical changes. An understanding of the overall process of sea water-crustal interaction and its effects on the four important processes enumerated above requires that both types of systems be investigated in detail. Crustal drilling is an essential tool for these studies because it is the best way of gaining access to the deep parts of these systems in order to sample the altered crust and circulating solutions and to measure in situ conditions and properties of the crust. Both products and ongoing processes can be investigated by drilling, and this information can be used to infer the structure and dynamics of these systems.

The critical questions revolve around two main issues: (1) what is the distribution of alteration in the crust with respect to intensity, depth, temperature, and other physical and chemical conditions and time? and (2) what is the relationship between hydrothermal activity and physical conditions within the crust, especially the heat source, permeability, and topography? Specific questions include: How deeply does water penetrate and why? How does this change with time? What are the major channels of permeability? To what extent are they eventually plugged and by what processes? Is high-temperature hydrothermal activity episodic? If so, what turns it on and off? How is it related to volcanism? Are crustal magma chambers episodic because of cooling by hydrothermal circulation? How pervasively is the crust altered and under what conditions? How does this affect the physical and chemical properties of the crust? Do sulfide mineral deposits commonly occur within the crust?

Modeling of crustal hydrothermal systems indicates that different chemical and physical conditions and processes can be expected within the downflow or recharge zone vs. the upflow or discharge zones. For example, anhydrite is likely to precipitate in large quantities in the downflow zones of the high-temperature systems, whereas quartz and metal sulfides are likely to precipitate in the upflow zones, at least during the waning stages of activity. The ultimate fate of this anhydrite has an important bearing on the geochemical cycle of sulfur and on the redox balance of the atmosphere-crust-ocean system over geologic time. Metal sulfide and quartz deposition are important for our understanding of ore genesis; fluid inclusion studies on quartz from silicified stockworks are a major source of data on conditions of ore deposition in hydrothermal ore deposits from many different geologic settings. Drilling a discharge zone of an active, high-temperature system on the sea floor could tell us whether quartz precipitation is an ongoing process and thus records the major period of sulfide mineral deposition, or whether most quartz is deposited only during the waning stage of activity.

Accordingly, a comprehensive drilling program would involve a series of holes in each of an active, high-temperature system and a passive, low-temperature system. These holes should be closely spaced, i.e., all within a few kilometers so as to intersect both the upflow and downflow zones of a system. For the passive system, holes should be located using heat-flow data. At least one hole in each system should penetrate 3 km or more into the crust in order to investigate the depth of water penetration and the distribution of alteration. The other holes should be about 1 km deep so as to completely penetrate the layer of pillow basalts. Ideally, these studies would be carried out on segments of both a fast-spreading ridge and a slow-spreading ridge. In addition, the studies should consider both open and sealed conditions, the latter occurring when a ridge segment is covered by sediment, as there is evidence from the geologic record that a sealed system may be conducive to formation of ore deposits.

In situ measurement of crustal properties and processes in the active, axial systems will require development of logging and sampling tools which can withstand temperatures above 350°C.

B.2 Important Problems

In addition to the two major questions of the origin and evolution of oceanic crust discussed above, we recognize several other very important ones which would be significantly advanced by drilling. Whereas the two major questions discussed earlier bear directly on the nature of the primary processes of formation of the ocean crust and the most important secondary process leading to its evolution, the additional important questions discussed below concern the nature, origin, and significance of other first-order components of the oceanic crust. We make no attempt to prioritize problems within this group.

Mantle Inhomogeneity and Mantle Evolution. Variations in isotopes and trace elements amongst basalts of mid-ocean ridges have been interpreted in terms of compositional heterogeneities in the source regions of the mantle. However, the extent of open-system fractionation and its possible role in decoupling incompatible and major elements in magma remain to be assessed. Similarly it has been proposed that the chemical variation of the primary melts can be explained by a varying depth of partial melting of the upper mantle in turn due to specific geodynamic conditions in the asthenosphere-lithosphere system. Thus one should now view mantle inhomogeneity as a useful working hypothesis with our present state of knowledge.

Chemical gradients along the ridges extending from the "hot spots" of Iceland and the Azores have been explained as resulting from mixing of "enriched" material from deep-mantle plumes with higher-level, normal "depleted" mantle. Deep-sea drilling has enabled basalts to be recovered from older regions of the ocean floor beneath the sediment cover, so that we can now monitor these compositional variations in space and time, as well as with depth, in the ocean floor. All this new information has produced a much more comprehensive picture of the nature and scale of mantle heterogeneity in the North Atlantic. More important, it is providing an insight into the causes of mantle heterogeneity and the physical and chemical processes which have been operating within the Earth's mantle, not only during the episode of sea-floor spreading of the last 150 m.y., but also the integrated effects during the last 4,000 m.y. At the moment our data base of basaltic material relating to this problem is significant only in part of the North Atlantic, a small fraction of the world's oceans. We need to extend our investigations into selected parts of the Pacific and Indian oceans if a full understanding of the physical and chemical evolution of the Earth's mantle is to be obtained.

Results so far from the North Atlantic have demonstrated that various sectors of the Atlantic have different and distinctive signatures of trace elements and isotopes. There are also consistent differences in the major element compositions of basaltic glasses. Determination of trace elements and isotopes in lavas from Atlantic Ocean islands has demonstrated that each ocean island has distinctive characteristics, so that earlier concepts that lavas from ocean islands were derived solely from a primitive source in the deep mantle through "plume" activity are now seen to be over-simplified. Mantle sources for basalts from the North-Atlantic Ridge and islands require a chemical and isotopic contribution from three or more components in order to explain the observed geochemical variations. Models accounting for these varying characteristics not only involve depleted source reservoirs in the mantle (which have evolved through extraction of continental crust through geological time) and more primitive mantle reservoirs, but may require recycling of lithosphere and continental material too.

We are only just beginning to understand the nature and scale of the processes required to explain these observations. It bears upon the whole problem of mantle dynamics and models of boundary-layer convection, the extent to which lithosphere is recycled and mixed back into the mantle reservoirs, and the processes of element transfer between different reservoirs through time. Other questions are raised. For instance, is the concentration of "hot spots" and enriched mid-ocean-ridge basalts in the Atlantic and around southern Africa, which presently corresponds to a geoid high, somehow related to the fact that the region was covered by the stable continental thermal carapace of Pangea since the mid-Palaeozoic? If so could the concentration of hotspot volcanic islands and oceanic platforms now in the southwest Pacific have been related to the Pacific geoid high? We know very little about these regions, but drilling could provide the essential information. Such models appear very speculative with the limited data base now available, but could be amplified, modified or discarded with equivalent data from regions other than the North Atlantic. Each new batch of data from drilling, dredging and on-land studies both constrains existing models and raises new factors which must be considered in framing new proposals for the physical and chemical evolution of the Earth's mantle.

This important problem must be seen as a natural continuation of the two high-priority interests. We need to understand the processes of magma generation in order to distinguish the effects produced by open- and closed-system fractionation, partial melting, and depth of magma generation from those resulting from heterogeneity of the mantle source. The "natural laboratory" for the study of mantle heterogeneity operates on a much larger scale. Drilling provides the only means of sampling basaltic lavas over vast portions of the ocean crust where such lavas are covered by sediments.

Crustal Aging. Hydrothermal circulation and its effects on the chemical and mineralogical composition of the oceanic crust, described in Section B.1, probably have causal relationships to observed variations in seismic velocity structure. The average seismic velocity in the upper few hundred meters of young crust is 3-4 km/sec and increases to a value usually greater than 5 km/sec in mature crust. It seems reasonable to assume that the first effect of aging on the young crust is a lowering of seismic velocity by weathering and alteration, and that after a certain age, cementing of rubble zones and sealing of fractures becomes the dominant process, with a resultant increase in seismic velocity. Sedimentation rates and crustal morphology probably have some control over the hydrothermal circulation, and hence may have an effect on the rate at which the original crust is modified, particularly after the crust is moved significantly away from the main heat source at the spreading axis. Drilling into slow- and fast-spreading crust of a variety of ages should permit these various causes and effects to be better understood.

Formation of Overly-Thick Crust and Flood-Type Volcanism. Next to ridge-crest volcanism, the second most significant form of volcanism on the earth is mid-plate volcanism occurring in the ocean basins. Such activity forms individual conical volcanoes, linear volcanic chains and clusters, giant oceanic plateaus and ridges, and thick intrusive complexes in the upper portions of the ocean crust.

Based on surveys, geophysical studies, drilling data, and studies of dredged rocks, it is now apparent that there was a remarkable episode of mid-plate volcanism near the center of the world ocean in Cretaceous times. Within a span of perhaps 30 m.y., the major guyot chains of the western Pacific, several large oceanic plateaus comparable in size to Iceland, and at least one major deep-sea intrusive and extrusive sequence were formed in an area of ocean crust as large as North America. Diverse magmatic products were erupted, and there were complex episodes of uplift and subsidence in different parts of the region whose timing and significance are still poorly understood. Volcanism in the region has been likened petrologically to that of linear island chains, to the rifts of East Africa, to Iceland, to continental plateau-basalt provinces, and to the ocean crust. Valid analogs to all these types of igneous provinces may indeed exist in this Cretaceous portion of the Pacific crust.

The volume of volcanism and types of rocks in the region imply that there was a major thermal and convective disturbance or series of events in the mantle that affected this portion of the globe. It may never be possible to unravel fully how this disturbance affected the various spreading-ridge segments and plates in the region. The volcanic rocks of the region, however, carry the geochemical imprint of their mantle sources, many of them showing the same enrichments in incompatible elements as lavas of linear island chains and the geochemical provinces of the North Atlantic. An important objective of crustal drilling should, therefore, be a systematic investigation of the composition, structure, and temporal relationships of the diverse plateaus, ridges, and basins of this region. The geochemistry of the samples will be important to compare with younger volcanic rocks in the oceans which may have resulted from comparable or smaller-scale disturbances in the mantle. The Cretaceous plateaus are targets of particular interest because of their bearing on problems of large-volume production of basalts in small areas of the ocean crust or the continents and because of uncertainty about the nature of deeper portions of the crust (are they fragments of continental crust carapaced with basalts, or are they truly oceanic in origin?).

The products of mid-plate volcanism represent important indirect samples of material beneath ocean crust away from mid-ocean ridges. Such samples are necessary to reconstruct the sizes, nature and geometrical relations of various mantle domains so they are important for mapping mantle heterogeneity. Mid-plate volcanism also represents a thermal perturbation to cooling ocean crust and lithosphere which may be exploited as a natural laboratory to study the properties and behavior of the ocean crust and lithosphere. Finally, dating mid-plate volcanism on linear ridges provides important constraints on absolute motions of the plates which in turn are critical to test plate dynamics models.

In addition to this major problem of mid-plate volcanism, we believe that younger seamounts on the ocean crust should be targeted for drilling. Lavas of these seamounts typically differ from those of the surrounding ocean floor, and they may represent sites of focused off-axis hydrothermal activity which may be quantitatively significant in cooling the oceanic lithosphere and in producing hydrothermal sedimentary deposits. Study of these seamounts is a logical complement to the study of the structure and hydrothermal processes of nearby spreading centers.

Transform Faults. Marine geological and geophysical studies over the past few decades have shown that crests of mid-ocean ridges are frequently offset by large transform faults. For example, the crest of the Mid-Atlantic Ridge is offset by a major transform fault about every 100-200 km of its length and smaller transform faults about every 50 km or so. Dredging of the steep scarps of transform faults has revealed a diverse suite of igneous and metamorphic rocks which include basalts, gabbros, and ultramafic rocks. The occurrence of gabbros and ultramafic rocks suggest that transform faults expose the lower parts of the oceanic crust and, perhaps, the upper mantle. Initially it was considered that faults with large throws had exposed the lower crustal rocks. However, detailed mapping of small-scale topography has shown that transform faults are associated with numerous faults of relatively small throw. Thus, oceanic crust may be unusually thin in the vicinity of transform faults, an observation that is supported by recent seismic refraction studies of the Kane Fracture Zone in the central North Atlantic. In addition, there is some evidence that transform faults may affect lava geochemistry and this may be particularly important in the North Atlantic where much of the crust is within the thermal influence of faults.

Though drilling has up to now played a small part in studies of transform faults, models of processes in zones of transform faults are now being developed which will be testable by drilling, despite the problem that many of the units in the fault zones are arranged vertically.

Drilling can test whether crustal units are indeed abnormally thin near zones of transform faults, can sample concealed blocks within the transform domain, and can investigate metamorphic and hydrothermal processes within such zones. The nature and age of sediment accumulations within basins on the slopes of fault troughs can also act as indicators of the timing and scope of fault movements in the zones. Thus drilling will be able to be planned to complement effectively the other geological and geophysical techniques used, and suitable targets will become available during the next few years.

Processes in Young Ocean Basins. The problems of young ocean basins span the divide between evolution of continental margins and oceanic crustal processes, and for this reason they may receive lower priority overall than other topics lying squarely within either field. However, the problems are pressing and important and deserve full consideration.

The early stages of splitting may be accompanied by continental twinning, early rifting, several stages of volcanism, and very high evaporitic or clastic sedimentation rates. As far as we know now any of these may be dominant during any splitting event, but recent drilling of sequences of dipping reflectors coupled with seismic surveying over a large number of margins suggests that the volcanic component may be more important than previously recognized.

Full sampling of the sequence of volcanism in a splitting environment would give important information about the tectonic environment of magma generation during the splitting process and hence about the process itself. The incidence of subaerial volcanism within the sequence of dipping reflectors of the Rockall margin suggests that near-Icelandic conditions may accompany the first stages of splitting, but the results from the Gulf of California drilling suggest that true oceanic magma-genic conditions set in very rapidly after that first phase. The timing of this evolution is crucial to a full understanding of the problem of splitting.

Hydrothermal and metamorphic processes are particularly important during rifting, especially where large inputs of sediment are taking place as in the Gulf of California. There Leg 65 drilling encountered apparently on-going greenschist-facies metamorphism. Hydrothermal deposits have been identified within the Gulf of California, and both open- and closed-system hydrothermal circulation are in progress there at present. The combination of thick, water-rich clastic sediments and volcanic accretion by intrusion of massive sills are clearly favorable environments for hydrothermal processes. Geophysical surveying may enable sites of precipitation of hydrothermal deposits to be identified, and these would clearly be prime targets for drilling. In addition, recharge zones would also be complementary targets if the full array of hydrothermal processes is to be investigated.

Clearly the Gulf of California is a prime target for this type of drilling, but other margins provide equally important targets where different aspects of this cluster of problems can be examined. This is particularly true of starved margins with dipping reflectors where the early stages of evolution can be sampled by a grid of holes of moderate depth, so that a picture of such a margin through time can be constructed.

Processes in Island Arcs and Backarc Basins. Many of the preconceived ideas about the make-up of the oceanic crust come from the picture that has emerged from studies of ophiolite complexes. It is now time that we reciprocate and study parts of the ocean floor which may be true analogs of ophiolites. Such regions could well be island arcs and/or backarc basins.

Backarc basins are loci of creation of oceanic crust. All the processes discussed above are therefore at play, but the unique environment, above a subducted slab of lithosphere with more abundant volatiles, may yield specific characteristics to the magmas produced in this environment and to the hydrothermal activity.

Two major problems concerning igneous activity along convergent margins in island arcs might be answered best by ocean drilling. These are temporal variations in arc volcanism and the nature of forearc volcanism.

Pulses or fluctuations in arc volcanism within a single arc and more globally are puzzling possibilities with very important implications for large-scale geodynamics. We are reasonably certain that in the Mariana Arc, for instance, the intensity of extensive igneous activity has fluctuated very markedly during the past 40 m.y., without any indication of coeval fluctuations in the rates of subduction. Some of the maxima appear to correlate with those discerned in other arcs on a global scale. Delineation of these fluctuations is not simple. Sampling too close to an igneous center produces biases from that center, both in quantity and temporally. At too great distances the effects become subtle and polluted by events in other arcs. An optimal target would be the volcaniclastic aprons behind the volcanic arc. These might be drilled fairly near their "heads" so that a clear record of fluctuations, but still with the integrative effects of mass transport of the volcaniclastics, would be obtained. In addition, drilling in these apron heads would show the temporal evolution of the arc geochemistry in coarser, volcanic detritus. Possibly interfering with this objective are metamorphic effects which would result from high heat flow in these glass-rich strata. Even this process would be valuable to explore as every oceanic arc ought to have such an apron, but few have been identified in old orogenic zones.

Forearc volcanism is a process discovered much by accident and for which we have no understanding. In the Japan Arc silicic activity was detected, whereas in the Mariana and Bonin arcs tholeiites and Boninites (Mg-rich andesite) were collected. Are these forearc eruptives manifestations of arc initiation, before that area becomes a province of low heat flow, or do they reflect some discrete, unusual event? We need to acquire a wide range of information about forearc volcanism but only drilling will provide a clear temporal history. Before drilling proceeds however, we need better (more detailed) surveys to locate forearc volcanic centers. Morphologic and magnetic studies appear to be the most promising approaches at this time.

Both of these areas can only be solved adequately with drilling but both, especially forearc volcanism, require very careful and extensive pre-drilling surveying, using not merely the conventional techniques but newer, more precise ones, such as transponder-navigated bottom and near-bottom studies, following SEABEAM delineation of the morphology and processed seismic reflection profiling.

C. DRILLING

C.1 General Statement

Investigation of the high-priority problems discussed above requires an integrated drilling program that will probe Layer 2 and as much of Layer 3 as technically possible. It will be necessary to examine a small number of well-selected sites in more detail than has been previously attempted. These sites should be as close to ridge axes as possible and representative of both fast- and slow-spreading centers, and should be selected only after extensive bathymetric, seismic, magnetic, and dredging surveys. They should also be situated to address as many objectives as possible including in-hole geophysical investigation. It will be useful to take advantage of previous drilling and oceanographic experiments such as those undertaken in the FAMOUS area and at DSDP Site 504.

Detailed geophysical studies are necessary prior to ocean-crust drilling. Seismic reflection and refraction studies have been a standard requirement for site selection of sedimentary rock drilling to demonstrate the areal extent of the units to be drilled. A similar level of knowledge about the oceanic crust is a necessity if the significance of the crust samples is to be understood. Detailed near-bottom multi-channel seismic reflection, seismic refraction, and magnetic surveys should be a minimum requirement. Block faulting in oceanic crust probably limits the lateral continuity to only a few kilometers or fraction of a kilometer for the upper acoustic units in oceanic crust. Detailed surveys over several crustal blocks (say 4 km x 4 km each) would provide key data concerning seismic velocities, areal extents of units to be drilled and estimation of the magnetic properties and their uniformity over a given block of crust. There is clearly a need here for a low-frequency source system with the capability to penetrate 2-3 km for the seismic near-bottom studies.

To investigate the wide range of problems discussed above the drilling at each site should consist of both shallow holes and a hole or holes drilled as deeply as technically possible. Drilling of Layer 3 is certainly a major objective, but if unattainable, many of the high-priority problems can still be addressed.

At each site several closely spaced holes of less than 1 km length will be needed to investigate the magmatic and tectonic processes and physical properties of the upper part of the crust and to provide a three-dimensional geologic context for interpretation of deeper holes, which ideally should be of the order of 3 km length.

C.2 Specific considerations

1. There is a strong need to drill bare rock for many of the high-priority, active-process oriented problems.
2. Drilling should be conceived as one component of a larger experiment including substantial geophysical and geological surveys conducted prior to drilling.
3. A downhole measurement program should be conducted both during and after drilling with re-entry holes left in a condition that permits reoccupation for further downhole measurements by conventional research vessels.
4. All holes should be continuously cored.
5. Holes should be designed for multi-objectives: e.g., a pattern of well-placed holes could be designed to test patterns of both hydrothermal convection and the shape of boundaries of magnetic reversals within the crust.
6. Where possible holes should be in high enough latitude to provide useful magnetic data.
7. At least one attempt should be made to drill as deeply as possible into Layer 3.

TECTONIC EVOLUTION OF CONTINENTAL MARGINS AND OCEANIC CRUST

A. INTRODUCTION

The development of the concept of plate tectonics in the late 1960's provided a general framework within which to explain observations from a wide range of disciplines in earth sciences, such as seismology, structural geology, and marine geophysics. Following the late 1960's, a number of large international programs were established to test and to examine the implications of plate tectonics; notably the Geodynamics Program, which emphasized the continents, the Joint Oceanographic Institutions Deep Earth Sampling (JOIDES) program, which concentrated on the oceans, and the NASA crustal dynamics program, which emphasized continents and oceans. These programs utilized new field techniques, such as seismic reflection profiling on land, dynamic positioning of drilling ships at sea, and very long baseline interferometry, providing important new observational constraints on the concept. Many questions remain, however, concerning the tectonic processes that occur within the plates and at the major boundaries of the plates.

This report summarizes some of the major scientific questions concerning the tectonic evolution of the world's ocean basins. We emphasize here those questions that appear to be particularly well-suited to be addressed in the future by drilling the deep crust. We point out, however, that drilling the deep crust represents one of a number of new technologies that will be available to the community of earth science in the next decade. We believe the development of other technologies, as well as quantitative modeling studies, is equally important to continue in the future in *conjunction* with a program of scientific ocean drilling.

B. IDENTIFICATION OF MAJOR TECTONIC PROBLEMS OF THE OCEANIC CRUST

During the past few decades marine geological and geophysical studies using seismic reflection and refraction techniques, direct sampling, in situ submersible observations, and deep-sea drilling have contributed substantially to our knowledge of the structure and composition of the oceanic crust.

The mid-ocean ridge systems are now considered to be the locus of crustal accretion, and we now know that the process of accretion is responsible for the creation of oceanic lithosphere. The relative motion across most of the world's systems of mid-ocean ridges has now been determined to a high precision (~0.1 cm/yr) by using lineation patterns of marine magnetic anomalies. We do not know, however, whether the motions across a ridge are episodic or continuous on short-times ($\lesssim 10^6$ years) since identifications of magnetic anomalies only provide an estimate of the *average* relative motion. The relative motion across a ridge system appears to be a strong control on the topography in the axis of accretion. Rifted ridges that spread at rates of $\lesssim 3$ cm/yr show a median valley about 2 km deep, an inner floor about 10-20 km wide, and rugged topography on the flanks. Ridges that spread at rates >3 cm/yr show an absence of a well-defined rift and relatively smooth topography on the flanks. Modeling studies have been carried out which attempt to explain these differences in topography, although little is currently known of the actual dynamics of the crests of mid-ocean ridges.

The material that is accreted at the crest of a mid-ocean ridge cools and subsides with time, forming the oceanic crust of the world's ocean basins. Direct in situ sampling by the Deep-Sea Drilling Project (DSDP) and submersibles shows that the upper several hundred meters of the oceanic crust consists mainly of extrusive pillow lavas and lava flows. By comparing the results of in situ sampling in oceanic regions with the results of studies of ophiolite complexes in continental regions (oceanic crust that has been emplaced on continental crust at convergent plate boundaries), some insight into the overall "stratigraphy" of the oceanic crust has now been gained. These comparative studies suggest that the thin basaltic cover grades into a complex of sheeted dykes at depths of about 0.8 to 1.2 km. This complex is characterized by greenschist- and amphibolite-grade metamorphic rocks and is underlain by a plutonic complex of mainly gabbroic rocks at depths of about 1.8 to 2.2 km. At deeper levels, the plutonic rocks grade into ultramafic rocks. Seismic reflection and refraction studies show that below a thin or absent layer of sediment the oceanic crust consists of an upper layer (Layer 2) with compressional wave velocity in the range 4.0 to 6.7 km/sec and a lower layer (Layer 3) with velocity 6.7 to 7.5 km/sec. The total thickness of the layers of the oceanic crust varies between different tectonic provinces, usually in the range 1 to 2 km (upper layer) to 3 to 5 km (lower layer). Recent studies, however, suggest that the velocity gradient increases steadily with depth in the upper "layer," and that below this the gradient decreases. Detailed comparisons of closely spaced velocity-depth sections show that the oceanic crust is highly heterogeneous in terms of its velocity structure and thickness and cannot, in fact, be characterized seismically into discreet layers.

Although thermal models explain the variation of sea-floor depth away from the crest of a mid-ocean ridge, as well as heat flow, gravity and geoid anomalies, the depth of large regions of the ocean basins cannot be explained by the thermal models. For example, the North Atlantic and the central Pacific oceans are shallower by about 1 km than they should be, while the southeast Indian Ocean and West Philippine Basin are too deep. Some of the largest regions of anomalous depths, however, occur at aseismic ridges and passive margins, where they can be attributed to variations in crustal thickness. Thus an important outstanding problem is to determine the thickness of the oceanic layer as a function of crustal age in order to separate the contributions of variations of crustal thickness to the depth of the ocean floor from other tectonic processes acting on the crust and lithosphere, such as convection in the layered mantle.

The synthesis of results of studies based on seismic reflection and refraction data, in-situ direct sampling, geological studies of ophiolite complexes and modeling studies of the subsidence of mid-ocean ridges has significantly improved our knowledge of the tectonic processes occurring in the oceanic crust. However, many questions remain concerning the tectonic evolution of the oceanic crust, the most outstanding of which are:

B.1 Dynamics of Magma Chambers and the Formation of the Oceanic Crust

The systems of mid-ocean ridges are characterized by a narrow zone of hot, upwelling asthenosphere extending from the base of the lithosphere to the oceanic crust. Within this "wedge" of hot material, partial melting leads to the formation of a basaltic magma. The basaltic magma appears to coalesce into small magma "pockets" forming bodies of various dimensions at shallow depths in the ocean crust. Since most models for the driving mechanism of plate tectonics involve processes in the mantle, the study of these shallow magma pockets is of particular current importance.

Scientific Questions

- *What is the nature and geometry of magma chambers that underlie the mid-ocean ridges?*
- *Is the magma chamber a steady-state feature?*
- *What are the geochemical processes occurring within the magma chamber?*
- *Do substantial differences exist between the nature and geometry of magma chambers beneath slow and fast spreading ridges?*

Solutions to Scientific Questions

- Detailed bathymetric and geological mapping of portions of the system of mid-ocean ridges using multi-beam swath mapping systems (SEABEAM), side-scan sonars (GLORIA and SEAMARK), towed vehicles (DEEP TOW), and manned submersibles (*Alvin*).
- Seismological studies to define the geometry of the magma chamber using arrays of ocean-bottom receivers and multichannel seismic arrays.
- Petrologic and geochemical studies of in situ bottom samples of basalts and glasses from mid-ocean ridges and continental ophiolite complexes.

Future Ocean Drilling

The determination of the compositional variations of basalts and glasses from mid-ocean ridges sampled by DSDP drilling, along with in situ samples obtained by dredging and submersibles, has provided some of the best information on magmatic processes occurring at a mid-ocean ridge. Future crustal drilling at the crests of mid-ocean ridges, we believe, will provide additional constraints on petrological, physical, and chemical models for magma generation at the boundaries of accreting plates. Of particular importance would be drilling zero-age crust at the ridge axis and drilling to deep levels in old oceanic crust.

B.2 Hydrothermal Circulation at Mid-Ocean Ridges

One of the most important discoveries concerning mid-ocean ridges during the past few years has been the evidence from heat-flow measurements and in situ samples from submersibles and DSDP drilling that hydrothermal circulation occurs in oceanic crust on a scale similar to that in hot spring areas, such as Rotorua in New Zealand and Yellowstone in the western United States. Hydrothermal circulation appears to cool the crust very effectively at the ridge axis, forming convection cells with narrow, upwelling limbs and downgoing limbs. Preliminary studies suggest that the spatial wavelength of the convection is a few kilometers and that it penetrates a few kilometers of the oceanic crust (Fig. 1). About 200 km^3 of ocean water has been estimated to pass through the oceanic crust each year, suggesting that hydrothermal circulation may be a major factor affecting the composition of the oceanic crust.

Scientific Questions

- *What is the nature of the hydrothermal "plumbing" system at the mid-ocean ridge?*
- *What is the horizontal and vertical extent of the circulation?*
- *What is the duration of "venting" of hot water at a mid-ocean ridge?*
- *What is the nature of metallogenesis at a mid-ocean ridge, and are massive deposits of sulphide (Kuroko) copper ore as abundant in the oceanic crust as they are in island arcs?*

Solutions to Scientific Questions

- Detailed heat-flow studies to determine the spatial and temporal variation of conductive and convective heat transfer in oceanic crust.
- Direct sampling and observation of hydrothermal vents on the ridge axis using submersibles.
- Crustal drilling to determine the geochemical properties of the hot water and hydrothermal precipitates.

Future Ocean Drilling

Drilling should be carried out in the future in active hydrothermal areas in order to determine information on the physical properties of the shallow crust and the geochemical processes occurring within the crust. Of particular importance are the porosity and permeability of the oceanic crustal rocks, since these properties determine the rate of flow of hot water through the crust, and geochemical processes, since they may control metallogenesis at a ridge. We believe that future crustal drilling at the ridge axis and older ridge flanks, combined with downhole geological and geophysical well logs, hydrofracturing, and azimuthally oriented photography experiments, will provide new constraints on the hydrothermal processes occurring at the ridge axis.

B.3 Composition and Structure of the Lower Oceanic Crust and Upper Mantle

The question of the composition and structure of the lower crust and upper mantle in oceanic areas has been one of the longest standing debates in marine geology and geophysics. Knowledge of the composi-

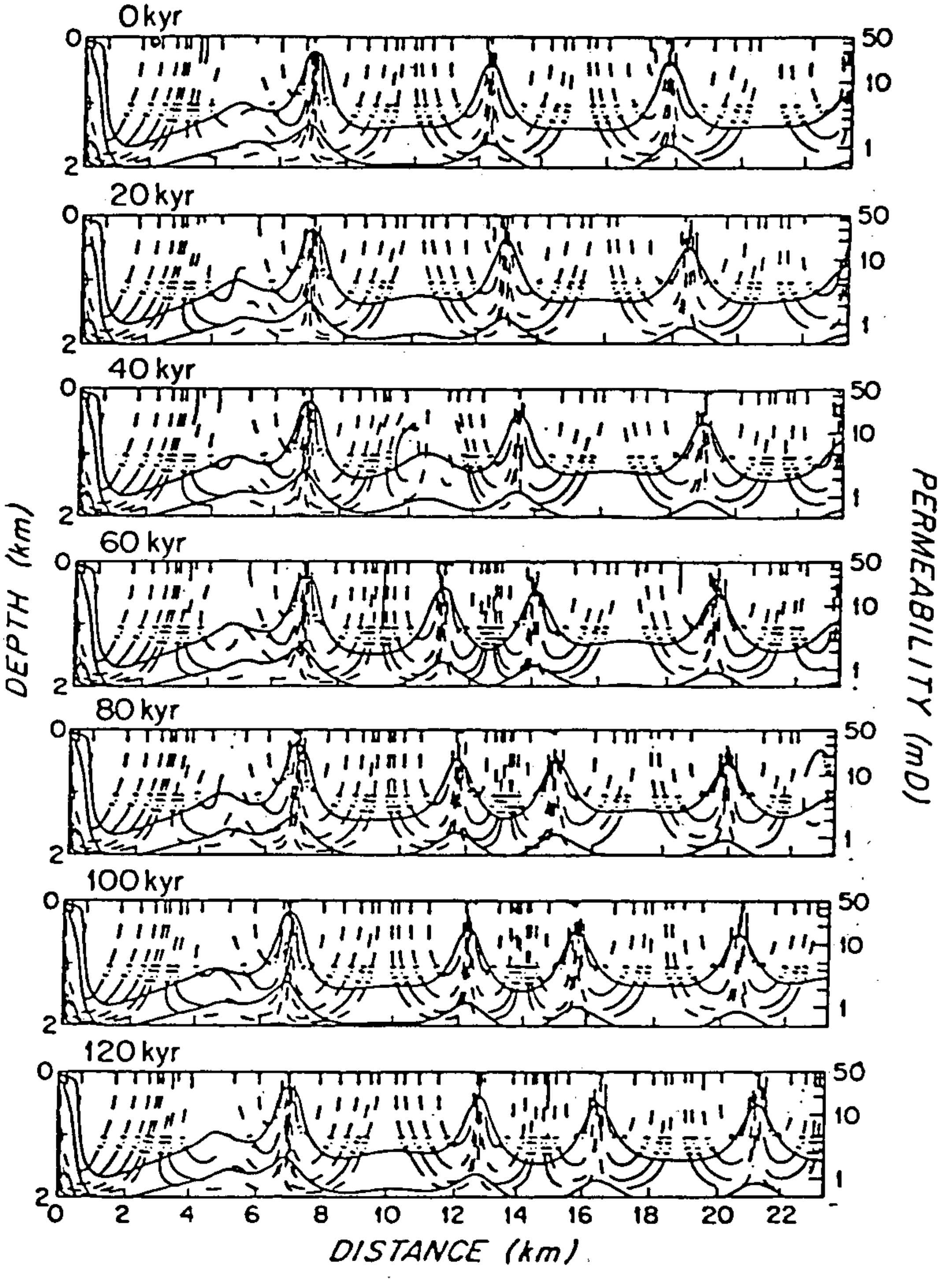


Figure 1. Finite difference models for porous media convection at a mid-ocean ridge system (from U. Fehn, University of Rochester, pers. commun.). The ridge crest is located at the left hand side of the models. The first cell is "stationary" because there is a continual heat supply at the ridge crest even though the crust is spreading to the right at about 3 cm/yr. The subsequent cells show sequential crust moving through relatively "fixed" cells. Only after 80,000 years do new cells break off and then spread outward with the crust. Thus each portion of the crust, according to the model, will experience both upwelling and downwelling of fluids at a mid-ocean ridge system. Deep crustal drilling out to about 20 km from the ridge axis would provide a critical test of these model calculations.

tion and structure of the lower crust is required in order to better understand the petrological, chemical, and thermal evolution of oceanic lithosphere.

A knowledge of crustal thickness is also of importance for studies of the tectonic evolution of oceanic crust. For example, the principal of isostasy suggests that each 1-km change in crustal thickness should be accompanied by a change of about 230 meters in

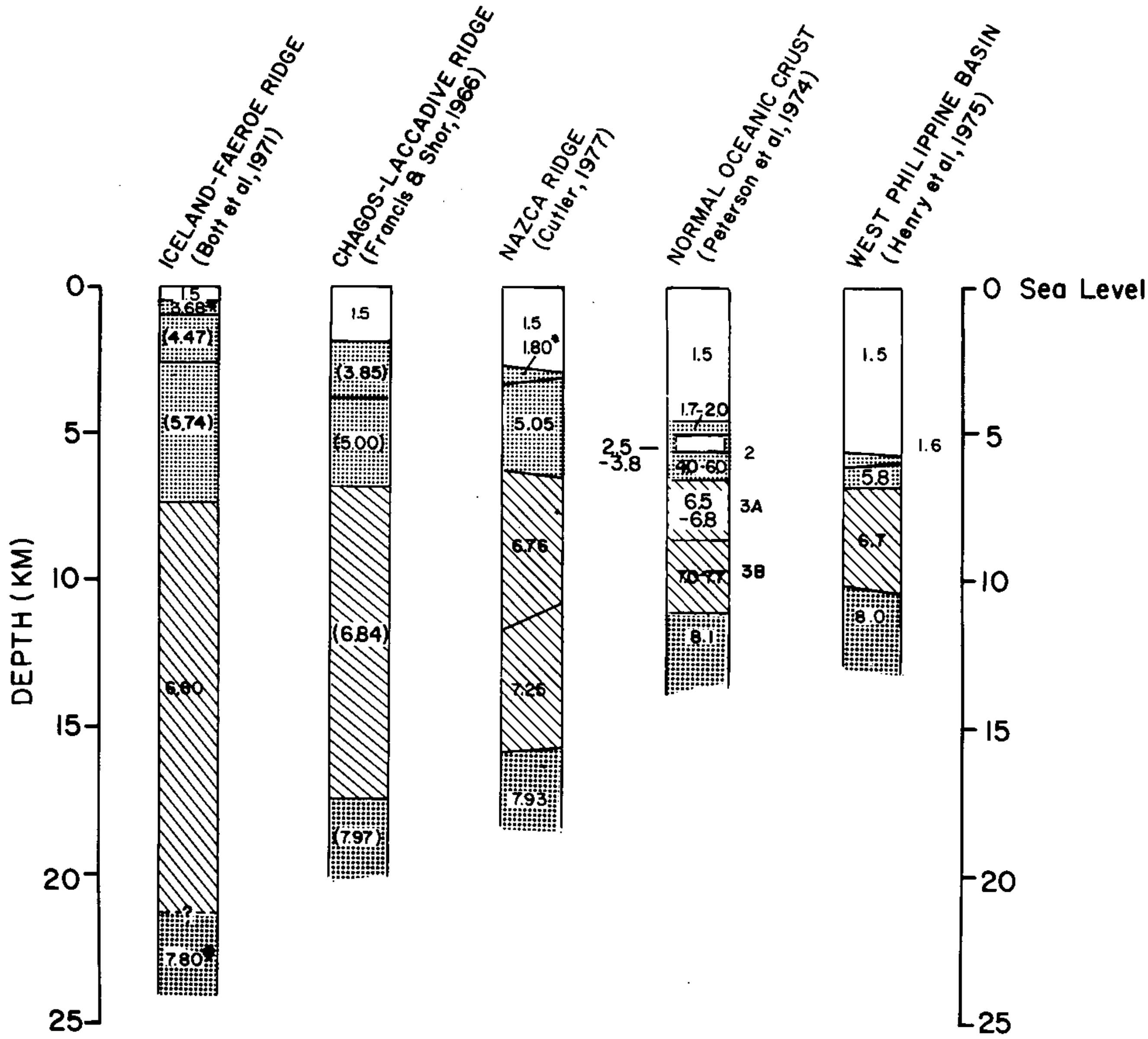


Figure 2. Schematic sections of the oceanic crust compiled from seismic data in the world's major ocean basins. Note the decrease in crustal thickness with increase in water depth due to isostasy. If it is assumed that the "normal" ocean-crust section is in equilibrium, however, then the West Philippine Basin is 1 to 2 km deeper than would be expected on the basis of isostasy (dashed line). Thus it is important to estimate accurately the crustal structure in the ocean basins in order to separate the effects of isostatic from non-isostatic, or tectonic, processes acting on the crust.

water depth. Fig. 2 shows that, in general, the oceanic crust thins as the water depth increases. However, in some regions, such as in the central Pacific Ocean, the crust is similar in thickness at depths of 4.5 km and 6.0 km. Thus processes other than changes in crustal thickness must cause the anomalously shallow depths in these regions. Better constraints on crustal structure in the oceans should enable us to understand and isolate these other tectonic processes.

Scientific Questions

- *What are the physical properties and compositions of the rocks that comprise the lower part of the oceanic crust?*
- *What is the nature of the Mohorovicic discontinuity (Moho)? Is it a compositional boundary separating ultrabasic rocks from more silicic rocks, or does it represent a phase-change boundary?*
- *What is the lateral extent of anomalous low-velocity zones in the lower crust and upper mantle? How laterally heterogeneous are the lower crust and upper mantle?*
- *What are the thickness of the lower crust and the depth to Moho in tectonically "active" areas such as systems of deep-sea trenches and outer rises, volcanic islands, and crests of mid-ocean ridges?*

Solutions to Scientific Questions

- Seismic refraction studies using large arrays of ocean-bottom receivers combined with sophisticated interpretation techniques of travel-time inversion and synthetic seismogram modeling.
- Multichannel seismic reflection studies designed to continuously profile sub-basement reflectors (especially Moho) and two-ship expanding spread experiments.
- Geological field studies of ophiolite complexes in mountain ranges.
- Deep crustal drilling combined with geological and geophysical downhole experiments such as borehole gravimeters and seismometers, hydrofracturing, and azimuthally oriented photography.

Future Ocean Drilling

Despite the rapid advances in the past two decades of the seismic structure of the oceanic crust and the processes occurring at the mid-ocean ridge, we still know relatively little of the physical properties and composition of the lower crust and upper mantle. Several deep drill holes penetrating the lower crust or the upper mantle would, we believe, provide information that could lead to major advances in our understanding of tectonic processes that form oceanic crust.

B.4 Structure, Petrology, and Geochemistry of Transform Faults and Fracture Zone Offsets

Marine geological and geophysical studies over the past few decades have shown that crests of mid-ocean ridges are frequently offset by large transform faults. For example, the crest of the Mid-Atlantic Ridge is offset by a major transform fault about every 100-200 km of its length. Dredging of the steep scarps of transform faults has revealed a diverse suite of igneous and metamorphic rocks which include basalts, gabbros, and ultramafic rocks. The occurrence of gabbros and ultramafic rocks suggests that transform faults expose the lower parts of the oceanic crust and, perhaps, the upper mantle. Initially it was considered that faults with large throws had exposed the lower crustal rocks. However, detailed mapping of small-scale topography has shown that transform faults are associated with numerous faults of relatively small throw. Thus oceanic crust may be unusually thin in the vicinity of transform faults, an observation that is supported by recent seismic refraction studies of the Kane Fracture Zone in the central North Atlantic (Fig. 3).

Scientific Questions

- *What is the tectonic and morphologic expression of the principal transform faults and fracture zones? What is the effect of spreading rate on the tectonic and morphologic expression?*
- *What is the extent and origin of anomalously thin crust within transform faults and fracture zones?*
- *What are the tectonics of the transform fault/spreading center intersections, and is the accretionary process at a spreading center altered in any way near the intersections?*
- *What is the nature of the basement ridges and "diapiric" structures within transform faults, and how were these features emplaced?*
- *What are the fundamental differences in geological processes such as metamorphism, hydrothermal circulation, isostasy, and volcanism in*

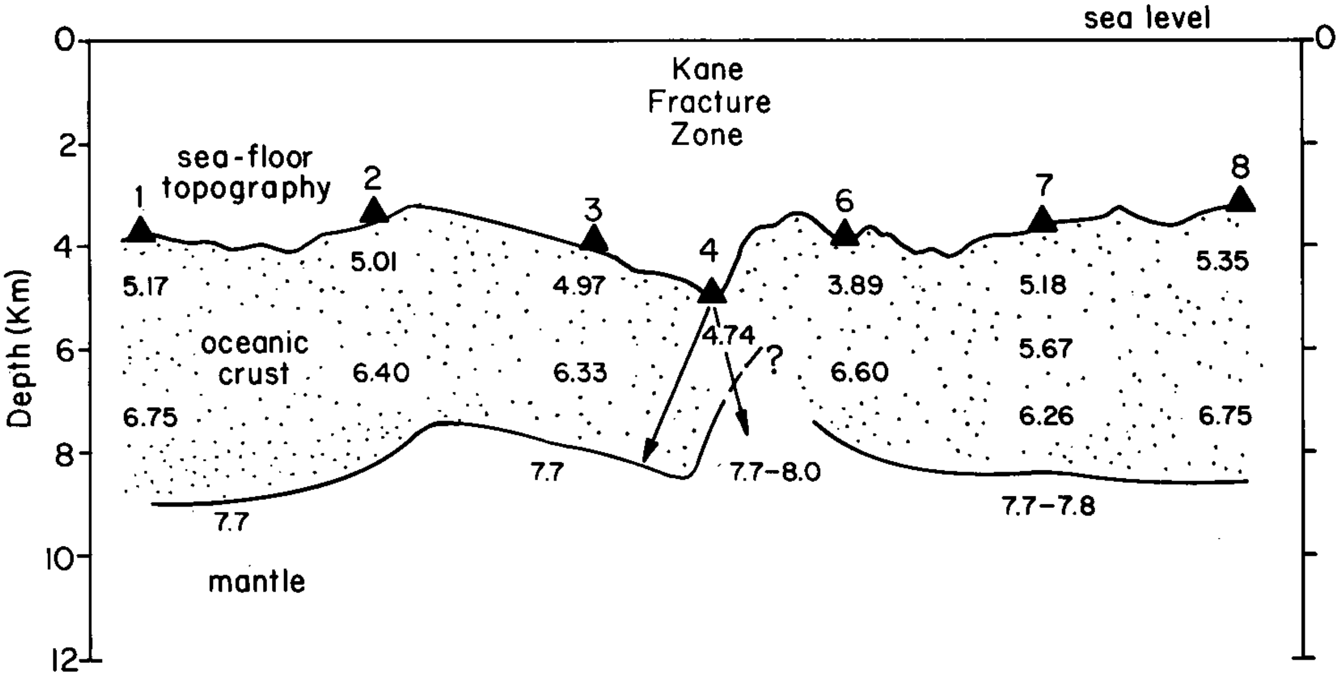


Figure 3. Schematic crustal section of the Kane Fracture Zone in the central North Atlantic (from Detrick and Purdy, 1980). This section shows a section of anomalously thin crust beneath the transform fault. Future drilling in the regions of the transform fault and flanking "normal" crust should reveal information on the tectonic processes causing crustal thinning at transform faults.

transform faults compared to normal oceanic crust?

Solutions to Scientific Questions

- Detailed geophysical surveying of transform faults and fracture zones using instruments such as multibeam echo-sounders (SEABEAM), side-scan sonars (GLORIA and SEAMARK), and DEEP TOW.
- Detailed sampling of rock outcrops within and adjacent to the transform zone using manned submersibles.
- Seismic refraction studies of the crustal structure proximal to transform faults and fracture zones using arrays of ocean-bottom receivers.
- Microseismicity studies of transform faults and the ridge/transform intersection using large arrays of ocean-bottom receivers.
- Deep crustal drilling to sample the crust within transform faults and fracture zones.

Future Ocean Drilling

Deep crustal drilling within transform faults in the future will address fundamental tectonic problems such as the origin of the anomalously thin crust and geochemistry of rocks within transform faults, the metamorphic and hydrothermal processes occurring in transform faults, and the nature of diapiric structures found within some transforms. Drilling would be most useful, however, only after similar deep crustal holes within "normal" oceanic crust have been completed and the structure and tectonic history of transforms have been better resolved using other geological and geophysical approaches.

B.5 Crustal Structure, Origin, and Tectonic Evolution of Oceanic Plateaus and Aseismic ridges

One of the more puzzling and controversial features of the ocean basins is the occurrence of a number of large submerged plateaus and ridges. These features, which typically rise about 2-3 km above the normal depth of the sea floor, are most common in the Pacific Ocean basin but also occur in the Atlantic, Caribbean, and Indian oceans. Among the most well-known plateaus and ridges are the Iceland-Faeroes Rise and Rockall Plateau in the Atlantic Ocean; the Seychelles Bank in the Indian Ocean; and the Shatsky Rise, Manihiki Plateau, and Ontong Java Plateau in the Pacific Ocean.

There is, unfortunately, too little seismic data available to determine unequivocally whether these features represent continental or oceanic fragments. The evidence that is available suggests that oceanic plateaus form either by fragmentation from continental land masses or by the piling up of volcanic flows, similar to present-day Iceland. The seismic structure of the Ontong Java Plateau, for example, reveals a thick layer of 6.1- to 6.3-km/sec material similar to that of the Rockall Plateau and Seychelles Bank, both of which are known from geological evidence to be continental in origin. The structure of the Iceland-Faeroe Rise, on the other hand, closely resembles that of Iceland, suggesting it formed by the pile-up of volcanic material at or near the crest of the Mid-Atlantic Ridge. A similar origin has been recently suggested for the Shatsky Rise and Manihiki Plateau, as well as other features in the Pacific Ocean (Line Islands Ridge, Hess Rise). These features have been interpreted as forming by the build-up of volcanic material on or near the Pacific/Farallon and Pacific/Phoenix plate boundaries about 90-120 m.y.B.P. Thus, like Iceland, they would represent abnormally thick and therefore buoyant oceanic crust.

The occurrence in the ocean basins of large regions of thick, volcanic material formed at a ridge crest has important geological and geophysical consequences since these features are nearly locally compensated, buoyant, and, therefore, would be relatively difficult to subduct. The subduction, or attempted subduction, of oceanic plateaus such as Shatsky Rise and Manihiki Plateau would be expected to have a profound effect on the tectonics of the associated island arc. A number of recent studies have proposed, in fact, that the Late Cretaceous/Early Cenozoic Laramide orogeny in the western United States may have been initiated by the attempted subduction of a large oceanic plateau that was a "twin" to the plateaus presently found in the central Pacific, such as Hess Rise.

Scientific Questions

- *What is the origin of oceanic plateaus and aseismic ridges? Do they represent continental fragments, such as Rockall Plateau and Seychelles Bank, or do they represent a large pile-up of volcanic material at or near the crest of a mid-ocean ridge, such as Iceland?*
- *What is the history of vertical movements (uplift and subsidence) of oceanic plateaus and aseismic ridges? Is the uplift and subsidence history what would be expected if these features formed on or near mid-ocean ridges and then subsided with time like normal oceanic crust, or is the uplift and subsidence history more characteristic of stretched continental crust? Alternatively, does the uplift and subsidence history of these features indicate vertical movements associated with a thermal resetting of the age of oceanic lithosphere?*
- *What are the consequences in the continents of the subduction or attempted subduction of oceanic plateaus and aseismic ridges? Do they control the tectonic features associated with low-angle subduction, such as the development of shallow dipping basement overthrusts? Do they form the allochthonous terranes that are important in continental accretion and mountain building?*

Solutions to Scientific Questions

- Marine geological and geophysical studies of oceanic plateaus and aseismic ridges in the Atlantic, Indian and Pacific oceans to define their morphology, crustal structure, age, and tectonic evolution.
- Studies of the relationship between gravity field, geoid, and bathymetry to determine whether these features formed on or near the crest of a mid-ocean ridge or off the ridge.
- Geological field mapping and palaeomagnetic studies of allochthonous material in the continents, particularly in western North and South America.

- Deep crustal drilling in oceanic plateaus to define the history of vertical movements that have characterized their evolution.

Future Ocean Drilling

Drilling on oceanic plateaus and aseismic ridges, such as 90° East Ridge, Walvis Ridge, Iceland-Faeroes Rise, Hess Rise, Shatsky Rise, and Manihiki Plateau, has revealed information on the history of subsidence and uplift and origin of these features (Fig. 4). The history of subsidence and uplift, however, may not by itself be able to distinguish whether these features represent continental fragments or thick, volcanic piles formed at or near the crest of a mid-ocean ridge, since continental fragments would have been extensively heated during rifting. The main evidence for the origin of these features is the composition of deep crustal rocks. For example, deep crustal drilling on select oceanic plateaus, such as Nazca Ridge, Hess Rise, Shatsky Rise, and Ontong Java Plateau, should reveal whether these features are continental or oceanic in origin. The drill data will also provide information on the age, history of subsidence, and uplift, and latitudinal motion of these features.

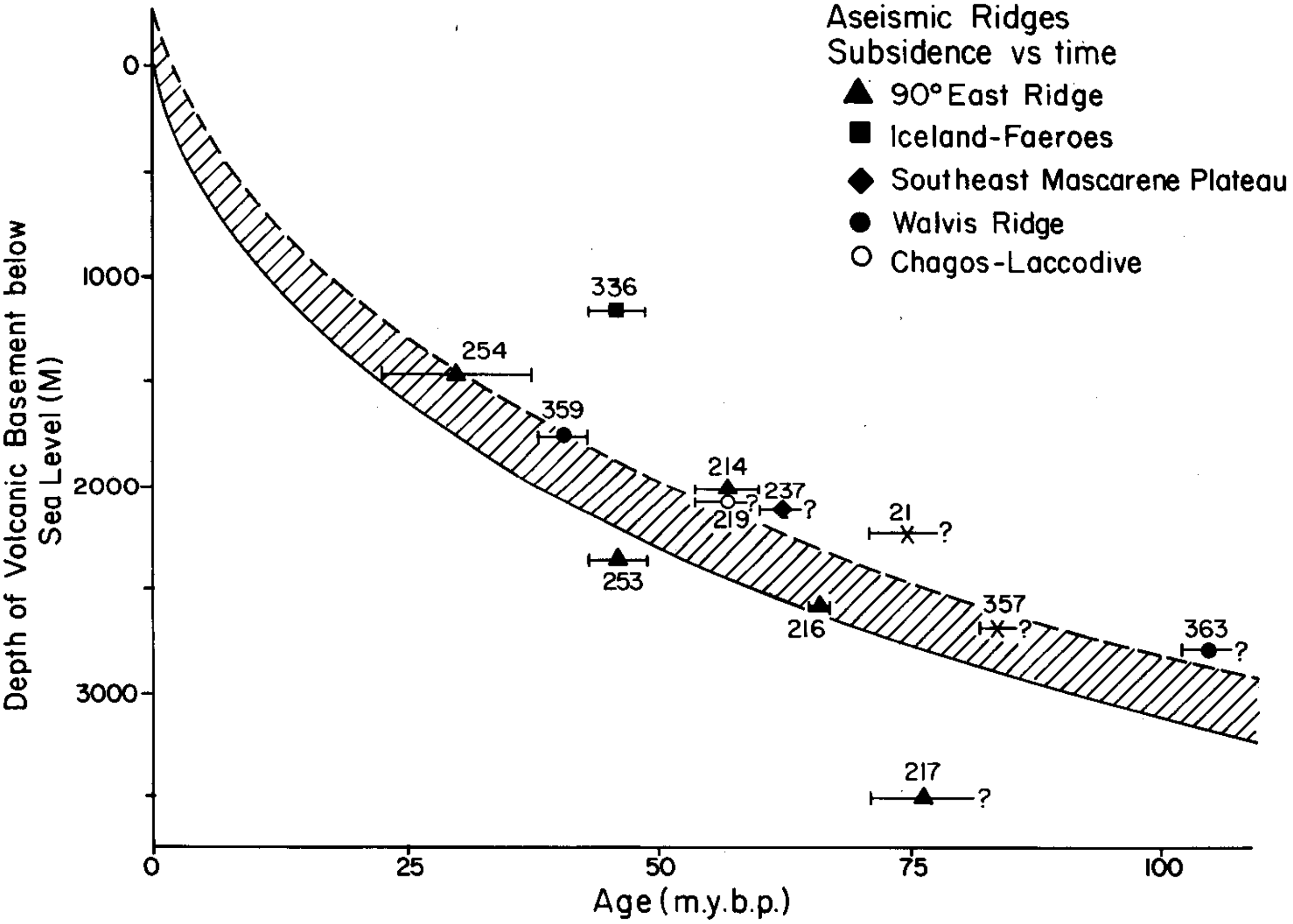


Figure 4. Subsidence history of select aseismic ridges in the Atlantic and Indian oceans based on deep-sea drilling (from Detrick et al., 1977). Note that most aseismic ridges generally follow the curve bow mid-ocean ridges (solid line) although some ridges appear to be about 0.5 km shallower than the ridge curve (dashed line). This could be due either to some ridges originating above sea level, which would delay the time of submergence of the feature, or to some form of tectonic process acting on the ridge after its formation. It is, therefore, important to document the subsidence of aseismic ridges in order to estimate the magnitude and form of these tectonic processes.

B.6 The Origin of Intraplate Volcanism

The ocean basins are characterized by a great diversity of volcanic features. Most active volcanism is associated with mid-ocean ridges and island arcs near the boundaries of the major plates. Many large volcanic features in the oceans, however, are located far from plate boundaries. A number of these features are younger than the underlying oceanic crust (for example, Hawaiian-Emperor Seamount Chain, Cook-Austral Islands), indicating that they formed by penetration of magma through the lithosphere in an "intraplate" tectonic setting.

The two main hypotheses that have been proposed to explain intraplate volcanism are the "hot spot," or "plume," hypothesis and the propagating fracture hypothesis. The former envisages a hot spot, fixed deep in Earth's mantle, which supplies magma to the base of the moving plate, while the latter proposes that the magma passively penetrates the plate through fractures caused by tensile failure of the lithosphere along pre-existing lines of weakness. These hypotheses have been successfully applied to a number of the *linear* seamount chains and oceanic island "ridges" in the ocean basins, such as the Kodiak-Bowie, Hawaiian-Emperor, and Easter Island chains.

The ocean basins (particularly the westernmost Pacific) are characterized, however, by numerous volcanic features which form *isolated* seamounts rather than linear chains. These features cannot easily be explained by either the hot-spot or propagating fracture hypotheses. The study of the age, evolution, and tectonic setting of these features may, therefore, provide important new constraints on models for intraplate volcanism.

Scientific Questions

- *What is the origin of intraplate volcanism? What proportion of volcanism in the ocean basins occurs in an intraplate setting?*
- *Is intraplate volcanism associated with a broad, regional uplift of the surrounding sea floor?*
- *What is the nature and extent of the intraplate volcanism that emplaced sills beneath deep water and which occurred during Cretaceous times in the central Pacific Ocean and the Caribbean?*
- *What is the cause of the widespread intraplate (as well as on-ridge) volcanism in the ocean basins in the Cretaceous? What is the relationship, if any, between intraplate volcanism in the oceans and the relative rise of sea level during the Cretaceous inferred from stratigraphic studies in the interior of continents?*
- *What is the origin of the apparent "western intensification" of volcanism in the Pacific Ocean?*

Solutions to Scientific Questions

- Detailed heat-flow and thermal modeling studies of well-known examples of intraplate volcanism, such as Hawaii and Bermuda.
- Dating of volcanic islands, island chains, and seamounts, especially in the western Pacific, using radiometric techniques of age dating on dredged or drilled samples.
- Drilling and dating of deep-water, intraplate volcanism, such as occurs in the Nauru Basin in the western Pacific.
- Seismic reflection profiling with large sound sources to map the seismic "reverberent layer," which may indicate the lateral and vertical extent of the deep-water, intraplate volcanism.
- Relative dating of features of unknown age and origin based on the flexural response of the lithosphere to loading.
- Petrological and geochemical studies of intraplate volcanic rocks.

Future Ocean Drilling

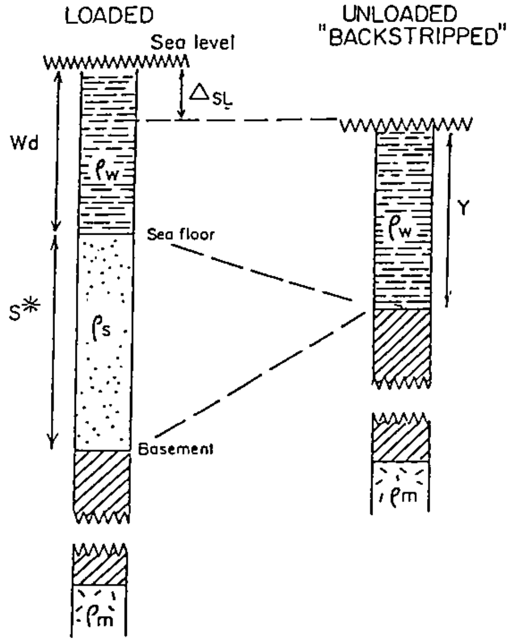
Future ocean drilling will be of particular importance in dating individual intraplate volcanic features in the world's ocean basins, as well as determining the uplift and subsidence history of broad regions of the sea floor affected by these events. Drilling is the principal means to address the problem of the age and origin of intraplate volcanism within the sedimentary column. The central Atlantic Basin in the region of Bermuda and the central Pacific Ocean in the region of the Nauru Basin appear to be the most promising areas for further detailed study.

C. IDENTIFICATION OF MAJOR TECTONIC PROBLEMS AT THE PASSIVE MARGINS OF CONTINENTS

The continental margins that border the world's ocean basins comprise some of the thickest sequences of sedimentary rocks that occur on the Earth's surface. These sediments provide a valuable record of the vertical and horizontal movements that have affected continental margins during their evolution. Passive (or Atlantic-type) continental margins are characterized by an absence of seismicity and mainly vertical movements. Active (or Pacific-type) margins, on the other hand, are characterized by abundant seismicity and both vertical and horizontal movements. The study of continental margins is of importance, therefore, because they contain some of the best evidence on the magnitude and form of the tectonic movements that have affected the Earth's crust during geological time.

The knowledge of the structure and tectonic evolution of passive margins has progressed rapidly during the past few years mainly due to technological advances in the dynamic positioning of drilling ships at sea and multichannel seismic reflection profiling. Commercial drilling in the coastal plain and continental shelf of relatively "old" passive margins, such as off the East Coast of the United States, Africa, and western Australia, has revealed detailed information on the history of postrift subsidence and uplift of passive margins. Similarly, commercial and DSDP drilling in "young" passive margins, such as Red Sea, Gulf of California, western Mediterranean, and south of Australia, have revealed information on the history of syn-rift or pre-rift subsidence and uplift of passive margins. Multichannel seismic reflection profiling by commercial, government, and academic groups on both "old" and "young" margins has enabled stratigraphic, lithologic, and palaeontologic correlation studies to be carried out over large regions of margins *between* drill sites. Broadly speaking, these studies show that passive margins comprise a gently dipping sequence of post-rift sediments overlying a fault-controlled syn-rift or pre-rift sequence. These sequences are separated at most margins by a "break-up" unconformity that approximately corresponds to the age of initial rifting and separation of the continental lithosphere. Data from drilling and seismic reflection profiling show that a substantial thickness of sediments can accumulate at a passive margin, exceeding 10 km at the relatively "old" margin off the East Coast, of the United States, and that a large proportion of these sediments form in shallow-water, marine environments. The principal of isostasy indicates that the weight of the sediments themselves is unlikely to cause thicknesses greater than 2½ times the water depth that is available. Therefore, the substantial thicknesses of sediments observed at passive margins cannot be caused by loading of sediments alone, and other factors must be involved.

Backstripping studies in which the effects of sedimentary processes, such as diagenesis, palaeobathymetry, and changes in sea level, are taken into account have revealed the form of the tectonic processes that affect passive margins through time (Fig. 5a, 5b).



$$Y(t) = F(D,t) * \left[S^*(t)\ \frac{(\rho_m-\rho_s(t))}{(\rho_m-\rho_w)}\quad \Delta_{SL}(t)\ \frac{\rho_w}{(\rho_m-\rho_w)}\right] + \left[Wd(t)-\Delta_{SL}(t)\right]$$

Basement Response **Sediment Loading** **Water Loading** **Water Depth**

Figure 5a. Schematic diagram illustrating the backstripping technique (from Steckler and Watts, 1978). The objective of backstripping is to obtain the tectonic subsidence (Y) of a basin by correcting observed stratigraphy for the effects of compaction (S*), changes in sea level (W_{SL}), and paleobathymetry (Wd). The tectonic subsidence can then be compared to the predictions of thermal and mechanical models for basin evolution.

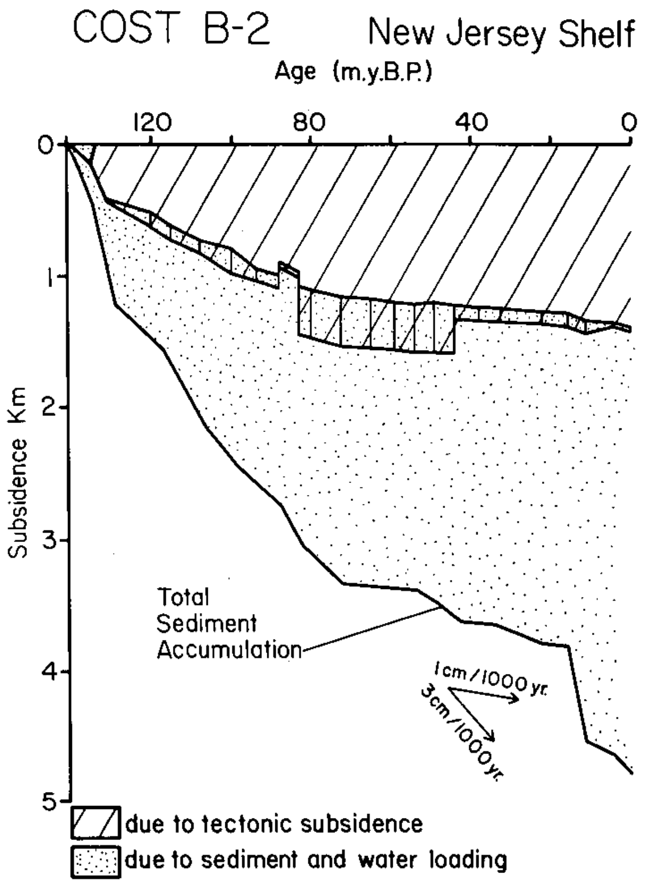


Figure 5b. Tectonic subsidence at the COST B-2 well (from Watts and Steckler, 1979). Note the relative proportions of the effects of tectonic processes and sedimentary loading at this well.

Although diagenesis, palaeobathymetry, and sea level contribute, these studies have shown that the main factors affecting the subsidence and uplift are sedimentary loading and thermal contraction.

Simple thermal and mechanical models which explain the main tectonic-stratigraphic features of passive margins have now been constructed. Thermal contraction in these models occurs following heating and stretching of the crust and lithosphere at the time of rifting, while sedimentary loading occurs by a broad, regional downwarping or flexure of the basement beneath the sediment load and a peripheral upwarping in flanking regions.

The thermal and mechanical model that best fits the stratigraphy of a passive margin is important to determine since it has implications for estimates of the magnitude of changes in sea level through geological time, the stratigraphy of unsurveyed margins, and the maturation history of the post-rift sediments. We currently have working models for the long-term variation of sea level through time and for calculating the temperature gradient and maturation history of sediments for different times since margin formation. However, a number of outstanding questions still remain at passive margins.

C.1 The Detailed History of Vertical Movements (uplift and subsidence) that occur at Passive Margins during their Evolution

The sediments which accumulate at a passive margin after rifting record the history of the tectonic movements that have affected the margin during its evolution. These tectonic movements are important to isolate since they can be directly compared to the movements predicted by different geophysical models for the origin of the margin. The stratigraphy of a margin, however, is the result of a number of geological processes, such as compaction, changes of paleobathymetry and sea level, and sedimentary loading, which interact with others during margin evolution. This interaction is not limited to the continent/ocean interface (or shoreline) but extends from the coastal plain to the deepest parts of the basin which is accumulating sediments. Thus, in order to isolate the tectonic movements at a passive margin, it is necessary to use backstripping techniques to correct the observed stratigraphy for these processes. Backstripping sedimentary and water loads progressively through time, however, requires detailed information on paleobathymetry, sediment porosity as a function of depth and time, long- and short-term variations of sea level, and the response of the basement to sediment and water loads as a function of position (Fig. 5a).

Scientific Questions

- *What is the form of the tectonic movements (uplift and subsidence) at a passive margin after corrections have been applied for compaction, sea level, paleobathymetry, and sediment and water loading?*
- *How do the tectonic movements vary across a margin?*
- *What is the nature of the response of the basement to sediment and water loads through time. Does the response vary as both a function of time and position across a margin?*

Solutions to scientific questions

- Backstripping studies of stratigraphic data at widely separated drill sites in passive margins using downhole geological and geophysical well logs.
- Studies of seismic reflection profiles to estimate the porosity-depth and paleobathymetry variations *between* drill sites.
- Oceanic and continental flexure studies to determine the nature of the response of the lithosphere at a passive margin to sediment and water loads through time.

Future ocean drilling

The analysis of stratigraphic data from deep crustal drill sites clearly plays a major role in addressing the problem of determining the magnitude and form of the tectonic movements that occur at passive margins. There already exist a substantial number of drill sites in passive margins. We believe that the systematic study of these data will significantly improve the current knowledge of the nature of vertical movements at passive margins. For example, sufficient data now exist from deep crustal holes in the passive margins off eastern North America, western Australia, and South Africa in order to address major scientific questions, such as the magnitude of long-term changes in sea level through time. Thus we see a role for future ocean drilling at a passive margin to address the problem of tectonic movements. However, this drilling should be *coordinated* with the data that already exist in land and sea regions from commercial wells and seismic reflection profiles.

C.2 The Deep Crustal Structure of Passive Margins

Most mechanisms for the origin of the large thickness of sediments that accumulate at a passive margin involve some form of extension or stretching of the crust and lithosphere at the time of rifting. The extension causes necking or thinning of the crust which subsequently subsides with time. Initially, there is a rapid subsidence of the crust (initial subsidence) due to the rise of hot asthenosphere material, followed by a slow subsidence as heat is conducted to the surface and the lithosphere cools (thermal subsidence).

There is now good observational evidence for crustal extension at the time of initial rifting at passive margins. The best evidence occurs at the relatively young margin off France and Spain where tilted fault blocks bounded by listric faults have been mapped (Fig. 6). Similar steep faults and narrow graben systems have also been mapped at the relatively old eastern North American and Brazil margins, although they are generally obscured by the thick sediments that form following initial rifting.

The stretching model has recently been applied to explain biostratigraphic data from deep wells in the eastern North American, western Mediterranean and Australian margins. The study of the Gulf of Lyon margin showed that the tectonic subsidence could be satisfactorily explained by the stretching model, although large amounts of extension by a factor of 2 to 6 were required. The main problem is that there is little geological evidence in the region for the large thicknesses of syn- and pre-rift sediments implied by these amounts of extension. Thus the geological evidence suggests a small amount of subsidence associated with rifting, while the tectonic subsidence requires

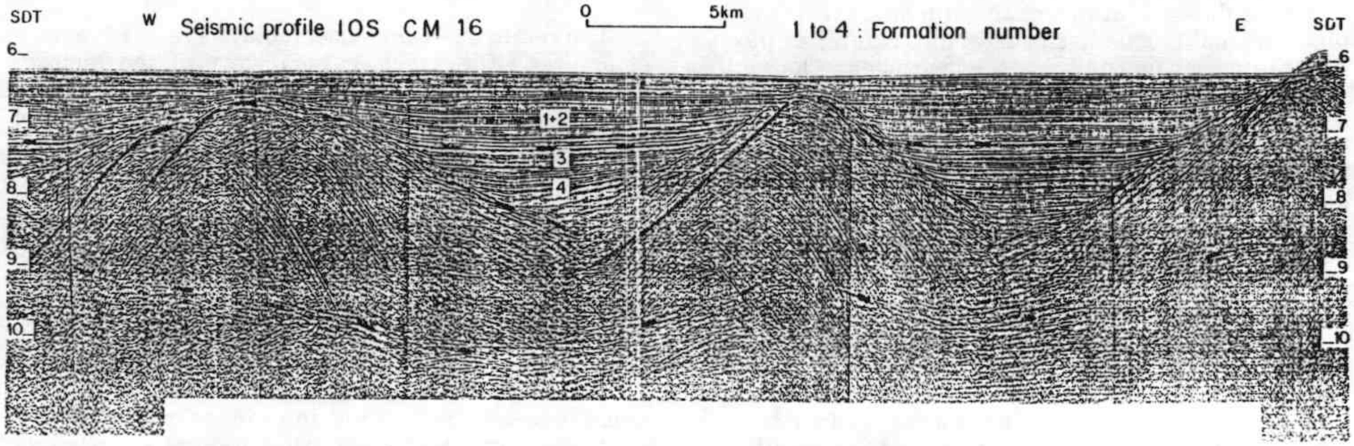


Figure 6. Seismic reflection profile of the northern Biscay passive margin south of Goban Spur showing tilted blocks with listric faults. Note the horizontal reflector observed over the deepest part of the margin below the tilted blocks. Drilling into these tilted blocks should reveal important information on the initial rifting processes at passive margins (from Montadert et al., 1979).

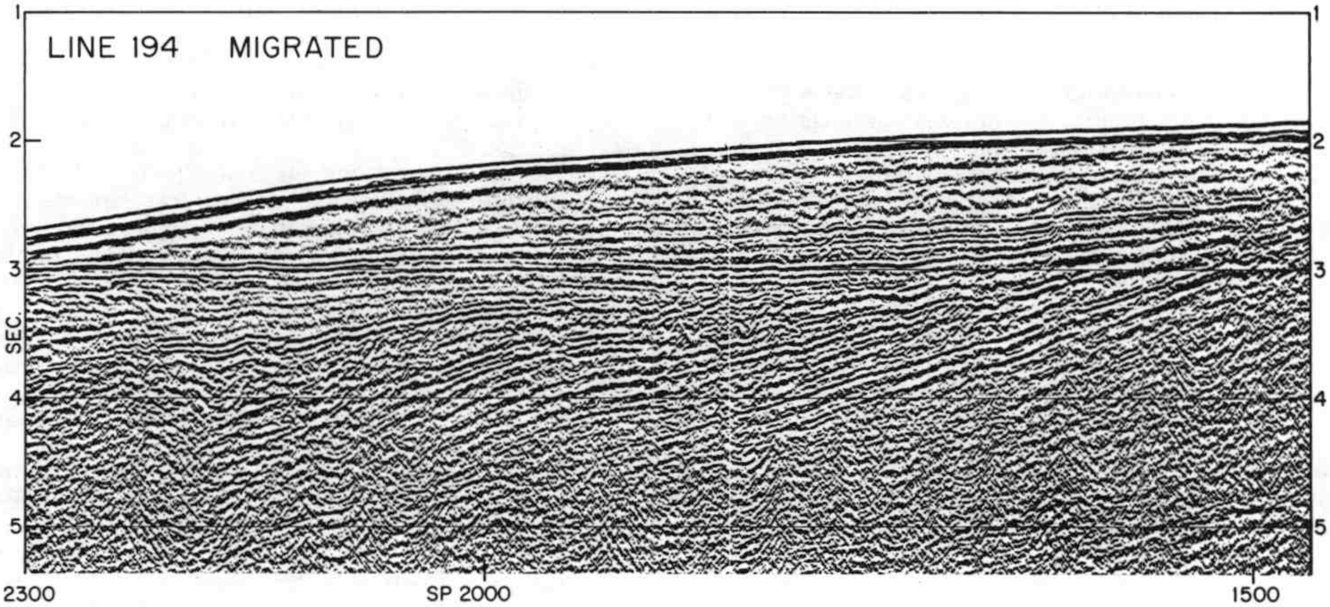


Figure 7. Seismic reflection profile of the Norwegian margin showing seaward dipping reflectors (from Mutter et al., 1982).

extensive heating during rifting. A similar problem occurs for well data in the Labrador margin. The stretching model has, therefore, been modified to include an upper and lower layer which respond to the extension by different amounts. This model, by a suitable choice of parameters, can produce a syn- and pre-rift elevation near sea level (and even uplift) followed by a post-rift subsidence.

The well-developed, tilted faults and listric faults, such as observed off France and Spain, are not seen at all passive margins. For example, seismic reflection profiles off Norway (Fig. 7), East Greenland, eastern North America and Antarctica show a well-developed sequence of seaward dipping reflectors along portions of these margins. Recent studies suggest these reflectors may represent layered volcanic rocks formed in a subaerial environment during initial rifting. It is not known, however, whether these volcanic rocks formed on pre-existing, unheated, continental crust or whether they formed in a pre-existing deep basin. The tectonic significance of the seaward dipping reflectors is, therefore, important to determine since they may indicate some form of active, rather than passive, heating at a margin.

The thermal model that best describes well data at a margin is important to determine since it has implications for the crustal structure and thermal history of the sediments at passive margins. Studies of well data have provided useful estimates of the amount of the crustal structure and thermal history at margins. However, it is important to constrain these estimates of the amount of thinning and heating using other geological and geophysical data, such as fault geometry, gravity and geoid, seismic refraction and reflection profiles, and heat flow data.

Scientific Questions

- *What is the lateral and vertical extent of thinned or heated crust at a passive margin?*
- *What is the detailed crustal structure in the region of the "hinge zone" that has been identified on multi-channel seismic reflection profiles of some margins? Is the hinge zone the major boundary separating relatively unstretched continental lithosphere from stretched lithosphere?*
- *What is the physical and chemical composition of the stretched crust at a margin?*
- *What is the relative proportion of syn- and pre-rift to post-rift sediments at a margin?*
- *What is the significance of the geophysical "edge" anomalies (gravity, magnetic, and heat flow) observed at some margins? Is the isostatic gravity anomaly observed at some margins the result of density differences within the crustal layer, sedimentary loading of a strong rigid basement, or temperature and density anomalies in the sub-oceanic mantle? Is the prominent magnetic anomaly observed at some margins the result of an edge effect between oceanic and continental crust, or does it result from magnetic sources within the sedimentary column? What is the contribution to observed heat flow at young margins (Red Sea, Gulf of Lyon) of lateral conduction of heat from the relatively hot, stretched crust to the cold, unstretched crust?*
- *What is the nature and origin of the Magnetic Quiet Zone (MQZ)?*
- *What variations occur in the physical and chemical properties in the deep lithosphere across a margin? Is there a difference in thickness and velocity structure between continental (old) and oceanic (young) lithosphere?*

Solutions to Scientific Questions

- Seismic reflection and refraction profiling using large aperture multichannel arrays and repetitive sound sources of sufficient resolution to define the rapid changes in depth to Moho that probably occur across the hinge zone.
- Deep crustal drilling to determine the age, depositional environments, and history of subsidence and uplift of the sediments that form during and

following initial rifting, and the physical properties of the stretched crust.

- Long seismic refraction profiles, teleseismic and surface wave studies (using earthquake sources), and magnetotelluric studies to determine the physical properties of the sub-oceanic and subcontinental mantle across a margin.
- Quantitative modeling studies to determine if the deep structure inferred from seismic and drilling data is consistent with gravity and geoid data across a margin.

Future Ocean Drilling

Future crustal drilling will be of particular importance in determining the deep structure of passive margins. The drilling should be focused to determine information on the relative proportion of syn-, pre- and post-rift sediments, as well as on the physical properties of stretched crust. Relatively young margins (Gulf of Lyon, Gulf of Valencia, Biscay) are the most promising since they are not obscured by large thicknesses of post-rift sediments.

C.3 The Thermal and Mechanical Evolution of Passive Margins

There has been a significant improvement during the past few years in our understanding of the thermal and mechanical evolution of passive margins. There have been two main reasons for this. First, technological advances in the dynamic positioning of drilling ships at sea and seismic reflection profiling techniques have improved knowledge of the shallow structure of margins. Second, models based on better constraints for the thermal and mechanical properties of the lithosphere have been constructed which can explain the overall tectonic-stratigraphic features of passive margins.

The thermal and mechanical models that best explain the stratigraphy of passive margins are important to determine since they allow predictions to be made about the deep crustal structure of margins, as well as about the temperature and maturation history of the sediments. For example, thermal and mechanical models for margin evolution predict that as a margin subsides following rifting, heat is lost vertically and horizontally as the lithosphere cools. The temperatures in the sediments can, therefore, be estimated for different times since margin formation if assumptions are made on the temperature at the surface of the sediments and the thermal properties of sediments and basement rocks. The temperature gradient in the sedimentary column is now widely believed to be one of the principal factors controlling the generation of mature hydrocarbons. Thermal and mechanical models can, therefore, provide a useful estimate, along with vitrinite reflectance and heat flow studies, of the maturation history of sediments at a margin.

Scientific Questions

- *What is the role of lithospheric flexure at passive margins? How does the flexural strength of the lithosphere vary as a function of time and position at a margin?*
- *What rheological model (or models) best describes the response of the lithosphere to extension at rifting and to sedimentary and water loading following rifting?*
- *What is the role of vertical and lateral heat conduction at a margin? How does lateral heat conduction vary as a function of time and position at a margin?*
- *How do flexural and thermal effects interact at a margin? Are thermoelastic effects important?*
- *What is the uncertainty in estimates that are based only on thermal and mechanical models of the maturation history at a margin?*

Solutions to scientific questions

- Measurements of subsidence and uplift in the flanking regions or "rims" of passive margins, such as the coastal plain and lower continental rise, since the effects of flexure and lateral heat conduction are greatest in these regions.
- Flexure studies in both oceans and continents in order to determine the response of the lithosphere to loads, such as ice-sheets and seamounts, which are of relatively short duration ($<10^6$ yr). Sediments represent loads that are being continuously added to the lithosphere, and it is often difficult at margins to separate tectonic from sedimentary effects.
- Quantitative modeling studies using simple models for histories of sediment loading and the "best fitting" thermal and mechanical properties of the lithosphere.

Future Ocean Drilling

Future ocean drilling will, we believe, provide information that will enable more refined models to be constructed for the evolution of passive margins. Of particular interest would be deep crustal drilling in the region of the hinge zone at relatively old margins (East Coast of the United States), since thermal and flexural effects are greatest in these regions.

C.4 "Global" Unconformities and the Synchroneity of Tectonic and Sea-Level Events at Passive Margins

One of the most important results of studies of existing commercial drilling and seismic data at passive margins has been the recognition by P.R. Vail and colleagues at Exxon of sequences bounded by unconformities on seismic reflection profiles. They used seismic reflection profile data as a "tool" to infer sedimentary facies through time by "calibrating" seismic stratigraphic sequences with the facies deduced from biostratigraphic studies of samples from nearby drill sites. By comparing the seismic stratigraphy from widely separated localities, they inferred that global (eustatic) changes of sea level are a major control on sedimentary sequences at passive margins. They used the seismic data to construct a "global" curve of sea level for the Phanerozoic (Fig. 8). A striking feature of this curve is the recognition of a number of slow rises in sea level followed by abrupt falls.

There is considerable debate at present, however, about whether the variations in sea level deduced by the Exxon group actually represent global changes in sea level. A major problem is that the data they used in their study is largely unpublished, and it is diffi-

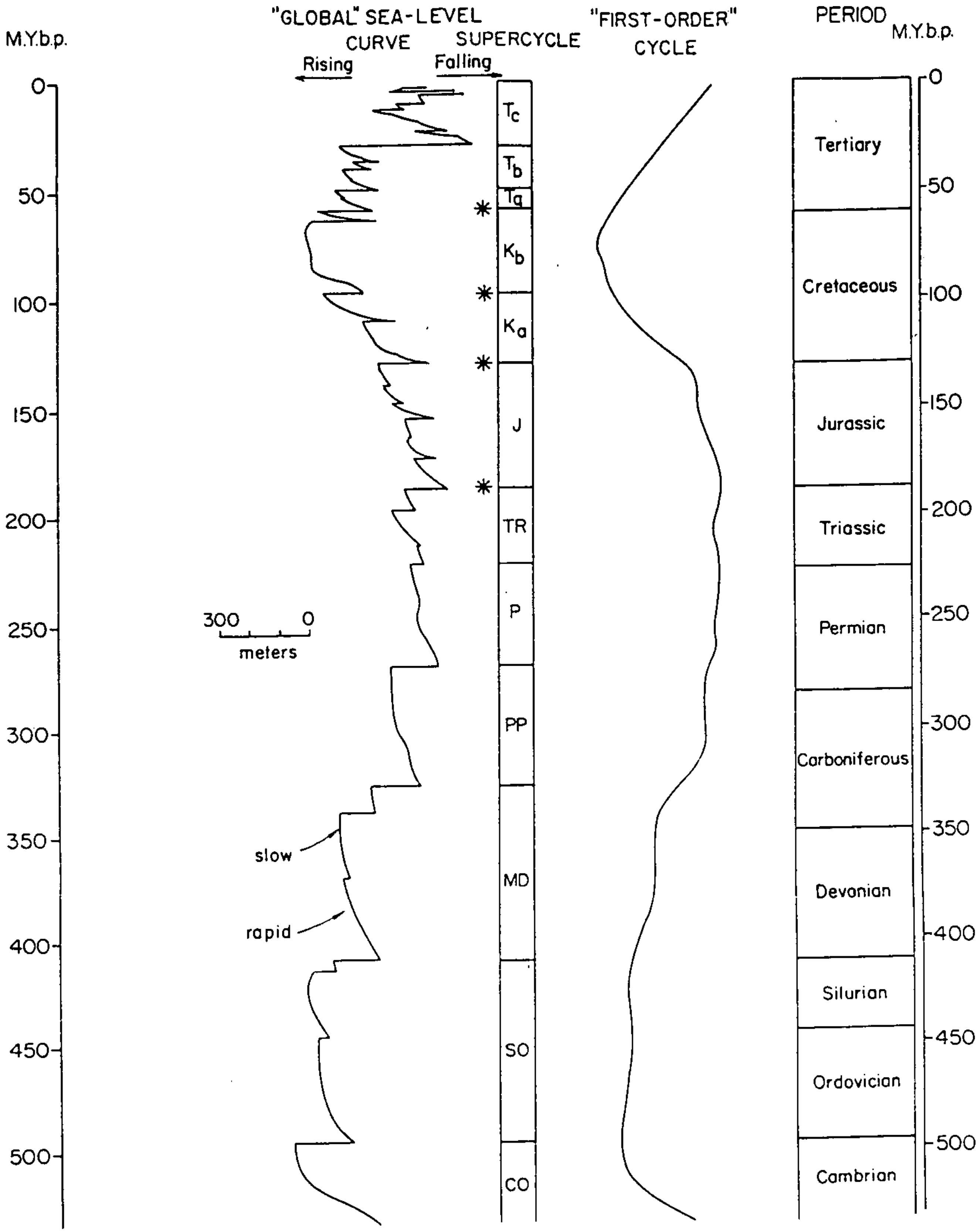


Figure 8. The "global" sea-level curve of Vail et al. (1977) showing the first-order cycle and the cycles that are superimposed on it.

cult to determine whether the effects of other factors that affect stratigraphy of passive margins, such as compaction, paleobathymetry, and sedimentary loading, were included.

The principal means by which the Exxon group estimated the rise and fall of sea level, in fact, was by recognition on seismic reflection profiles of coastal "onlap" and "offlap." They used some form of a weighted average of estimates of coastal onlap and offlap from seismic profiles at different passive margins to infer the rise and fall of sea level. The occurrence of coastal onlap and offlap in the stratigraphic sequences does not, however, necessarily indicate changes in sea level. The variations in sea level mapped by the Exxon group may correspond to events of widespread subsidence and uplift at passive margins. For example, most thermal and mechanical models for the evolution of margins assume that the flexural strength of the basement increases with time following margin formation as the lithosphere cools. Sedimentary loading of a basement that increases its flexural strength with time produces coastal onlap, similar in form to that determined by the Exxon group based on seismic profiles. The model studies suggest, therefore, that a margin should show coastal onlap soon after rifting as the lithosphere cools. Since many margins rifted at similar times (for example, Australia-Antarctica, Newfoundland-Britain), the onlap would be expected to be widepread, but it would not necessarily be worldwide.

Scientific Questions

- *What is the significance of sequences bounded by unconformities at passive margins? Do they have a tectonic or eustatic control?*
- *To what extent can sequences bounded by unconformities be correlated at passive margins?*
- *What is the contribution of the increase of flexural strength of the lithosphere with time to coastal onlap at passive margins?*
- *What is the cause of coastal offlap?*
- *What is the contribution to changes in sea level of changes in volume of mid-ocean ridges, volcanism, mountain building, and glaciation? What effect do these changes have on the stratigraphy of passive margins?*

Solutions to scientific questions

- Quantitative modeling studies of margin evolution that take into account the rheological zonation of the lithosphere, lateral flexure, heat conduction, and erosion.
- More refined global models for calculating the contribution to sea level of changes in volume of mid-ocean ridges, volcanism, mountain building, and glaciation.
- Drilling *and* seismic reflection profile data from widely spaced passive margins.
- Detailed biostratigraphic studies of prominent sequences bounded by unconformities (such as the mid-Oligocene unconformity) at widely spaced passive margins. The studies should determine as accurately as possible (to a resolution of better than 0.5 m.y.) the paleobathymetry of stratigraphic sequences above and below the unconformity so that effects of sea level and tectonics may be separated.

Future Ocean Drilling

The success of the Exxon group at identifying widespread and, perhaps, worldwide unconformities can largely be attributed to their access to both drilling *and* seismic reflection profile data from widely separated passive margins. Thus, future ocean drilling at margins should be coordinated to take into account the existing drill and seismic data from land as well as ocean areas. We believe a coordinated program of ocean drilling in widely separated margins could provide important information in the future on the nature of the control (tectonic or eustatic) on stratigraphic sequences.

D. IDENTIFICATION OF MAJOR TECTONIC PROBLEMS AT THE ACTIVE MARGINS OF CONTINENTS

The knowledge of the tectonic evolution of active margins has progressed rapidly during the past few years mainly as a result of seismic reflection and refraction profiling studies, deep crustal drilling, and teleseismic studies using earthquakes as sources. The main tectonic features of active margins are a volcanic island arc, a wide forearc region, often composed of deformed sedimentary rocks, a deep-sea trench, thrust-type and deep earthquakes, and large-amplitude geoid and gravity anomalies. Active margins occur at convergent plate boundaries and are recognized as sites of crustal consumption by processes referred to as subduction. Subduction is a critical part of the cycle of plate tectonics in that it results in the closure of ocean basins and provides a direct mechanism for the formation of oceanic belts.

Active margins, in fact, are characterized by a diversity of tectonic features and geological processes. Broadly speaking, there are two main types of tectonic setting of active margins. The Arc-type occurs in an oceanic setting and consists of a frontal island arc and deep-sea trench separating an oceanic backarc basin from the main ocean basin. The Andean-type margin occurs in an oceanic/continental setting and consists of a continental arc and deep-sea trench. These two basic types of active margin show a large diversity along individual arc systems. Either type may have a wide or narrow forearc zone. Either may show compression, extension, or quiescence in the backarc region. Finally, a wide variety of volcanic types are associated with active margin environments. Thus, there has been considerable geological interest in recent years on the structure, composition, and evolution of systems of active margins.

D.1 The Structure and Evolution of Forearc Regions

For over a decade we have known that material is accreted from the downgoing plate to the overlying plate during convergence. We have discovered only recently, though the combination of excellent seismic reflection data and deep-sea drilling, that many convergent margins accrete little material, and some may be undergoing tectonic erosion. Some accretionary margins, such as the Lesser Antilles, have accretionary wedges over 200 km wide and up to 20 km thick. Others, such as the Peru and Japan margins, have wedges only 20-30 km wide and 2-3 km thick. Accretionary wedges show abundant evidence of long-term uplift, whereas non-accretionary forearcs show substantial subsidence.

It has been suspected for many years that thrusting, in general, and particularly in subduction zones, is affected by overpressured pore fluids. Elevated pore pressures of lithostatic proportions were measured on DSDP Leg 78A in the Barbados subduction zone.

Quantitative modeling of the mechanics of subduction zones requires an understanding of the degree of lithification and the fluid pressures in the subducted sediments. Initially, tectonic compaction causes dewatering, the degree of which depends upon the presence of high-permeability pathways. If the pathways are lacking, overpressuring could occur at shallow depths of burial. Furthermore, at depth (temperature greater than 60°C) the dehydration of clay minerals and the breakdown of organic matter would also contribute to the pore fluid. Generally, high fluid pressures are expected at depth in order to account for the lack of seismicity and low heat flow in the upper parts of subduction zones.

Whether subducted sediments are offscraped in discrete fold or thrust packets or are zones of distributed deformation (flow) depends upon the degree of lithification. At low temperatures lithification occurs primarily by the precipitation of cement from fluids migrating from depth or local pressure solutions. Both processes slow to a rate governed by the rate of fluid dissipation when fluid pressures rise to lithostatic values. Therefore, the rate of fluid migration is one of the primary controls on the mechanical behavior of subducted sediments. Moreover, modeling of the thermal structure of subduction complexes requires information on the rates and depths from which fluids migrate.

Scientific Questions

- *How are pore pressures distributed in a subduction zone?*
- *What is the relationship between the geometry of the subduction beds, rock composition, and the pathways of fluid migration?*
- *Do faults enhance dewatering by providing high-permeability pathways or hinder dewatering by disrupting the beds?*
- *How does the migration of pore fluid relate to diagenesis of subducted sediment and to changes in physical properties?*
- *Is fluid migration primarily parallel to layering or vertical through the sediment wedge? How is this related to the degree of disruption of the beds?*
- *How does pore pressure influence tectonism in subduction zones?*
- *How do large quantities of expelled fluids escape through the slope cover of the trench wall?*

Solutions to Scientific Questions

- Data from deep and shallow drilling to study:
  a) porosity and permeability of recently underthrust sediments filling trenches;
  b) temperatures and compositions of the fluids and how they vary between layers;
  c) initial depth to overpressuring;
  d) rates and volumes of fluid flow through specific overpressured horizons;
  e) rocks from subduction complexes to establish mineralogy and structures caused by hydrologic and hydrothermal processes.
- Quantitative modeling to find the limiting conditions of hydrologic environments in subduction zones.
- Detailed seismic reflection and multibeam echosounder studies to establish detailed control of surface and near-surface structure.

D.2 Tectonic Evolution of Backarc Basins

The small, semi-enclosed basins (or backarc basins) that occur behind some island arcs have long been recognized as important features of active margins. Seismic refraction studies and petrology of in situ samples indicate that the crust of these backarc basins is oceanic. Backarc basins have been formed by crustal extension, by trapping of a piece of older oceanic crust behind a newly formed arc, and by closing of a larger basin behind an arc. Drilling data suggest that backarc basins subside in a manner similar to that of normal oceanic crust, although some basins are deeper than would be expected.

The main problem at present is to explain the factors that govern the development of extension, compression, or quiescence in backarc regions. From examination of modern arc systems, it appears that a given arc may undergo changes through time from one mode to another.

Scientific Questions

- *What are the causes of crustal extension and compression in backarc regions?*
- *What are the temporal relationships between arc volcanism, subduction processes (e.g., accretion vs. non-accretion), and backarc extension and compression? Are these related to parameters of subduction (rate, direction, dip, and geology of the incoming plate)?*
- *What is the nature of the accretion process in backarc basins, and how similar is it to processes occurring at "normal" ocean-ridge systems?*
- *What is the nature of the convergence processes in backarc regions, and how is it similar to or different from processes occurring in forearc zones?*

Solutions to Scientific Questions

- Marine geological and geophysical studies of active backarc basins using multibeam echosounders, DEEP TOW, and manned submersibles.
- Deep crustal drilling to determine the composition and age of the crust of backarc basins and sedimentary rocks and to examine the structure, age, and physical properties of material deformed by processes of backarc convergence.

D.3 The Detailed History of Vertical Movements (uplift and subsidence) of the Forearc

One of the most important results of recent drilling in active margins has been the recognition that the forearc region (arc-trench region) of island arc-trench systems and continental arc-trench systems is characterized by a significant tectonic subsidence. Traditionally, the forearc region has been considered to be dominated by crustal accretion and tectonic uplift. The extent of accretion is indicated in seismic reflection and gravity anomaly profiles by the greater overall width of the forearc regions in relatively old island arcs than in the young arcs. Tectonic uplift is indicated in bathymetric profiles, which show a break in the slope of the trench, and in uplifted marine terraces of oceanic islands (such as Bonin, Lesser Kuril). Recent drilling, however, has revealed a tectonic subsidence of about 2.2 km since the Oligocene in the Japan Forearc (Figs. 9, 10). This magnitude for the tectonic subsidence exceeds that which would be expected for a mid-ocean ridge, providing an important new constraint on thermal and mechanical models for subduction.

Scientific Questions

- *What is the form of the vertical movements (uplift and subsidence) in the forearc?*
- *What is the origin of the rapid subsidence of the forearc that appears to follow the initiation of subduction?*
- *What role do thermal effects play in determining the history of subsidence and uplift of the forearc?*
- *What role do mechanical effects play in determining the history of subsidence and uplift of the forearc?*

Solutions to Scientific Questions

- Backstripping studies of stratigraphic data at drill sites in forearc regions using downhole geological and geophysical well logs.
- Studies of seismic reflection profiles to estimate the porosity versus depth and, possibly, paleobathymetry variations between drill sites.
- Quantitative modeling studies to determine the relative contribution of thermal effects, such as the cold, downgoing lithospheric slab, and mechanical effects, such as crustal "underplating," to the vertical movements (uplift and subsidence) in the forearc.

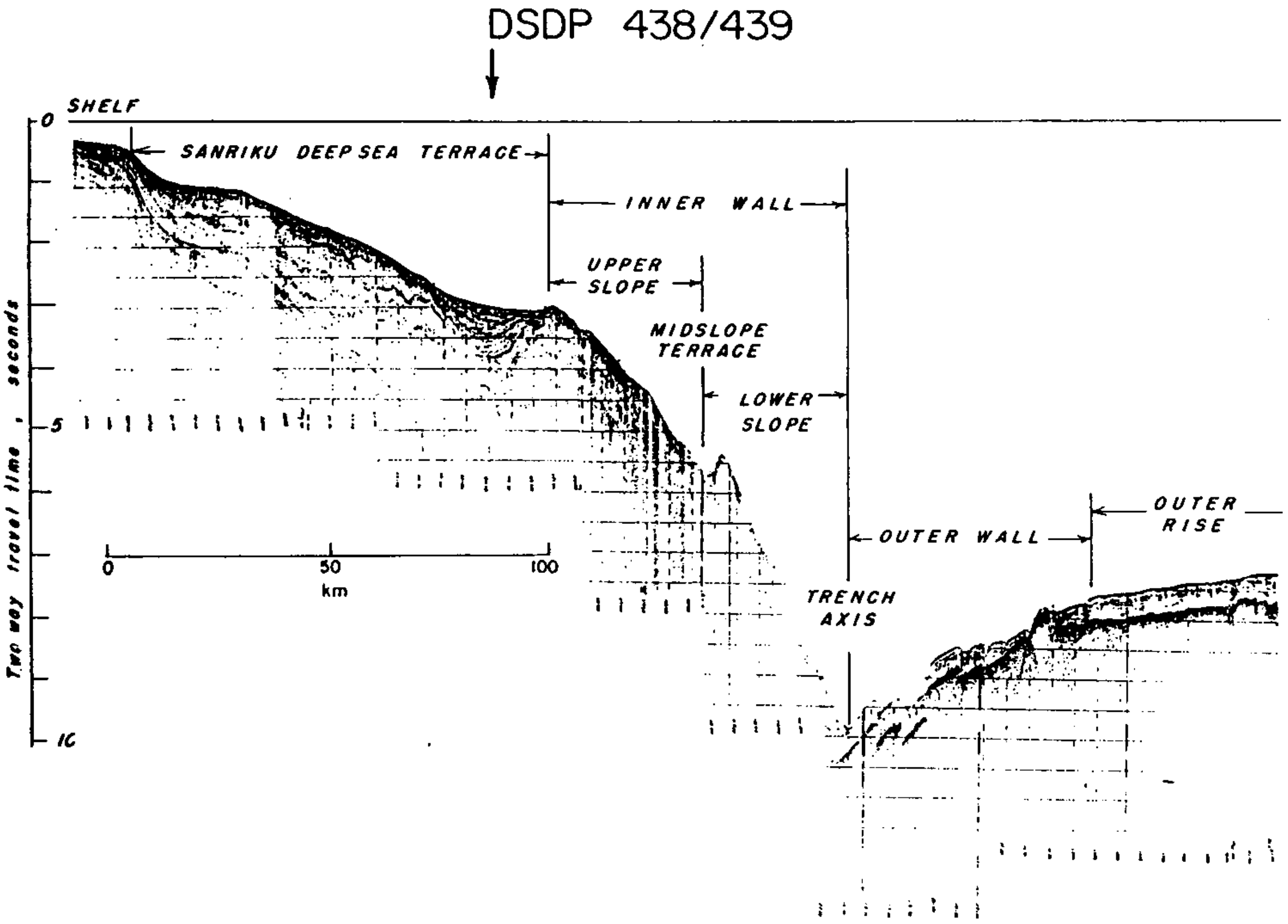


Figure 9. Seismic reflection profile across the Japan transect showing the approximate location of DSDP Site 438/439 drilled on Legs 56 and 57 of *Glomar Challenger* **(from Langseth et al., 1981).**

- Oceanic and continental flexure studies to estimate the nature of the response of the lithosphere in the forearc to sedimentary loading.

Future Ocean Drilling

The recent data from drilling in the Japan Forearc (Figs. 8 and 9) suggest a major role for future ocean drilling at active margins. Drilling is the principal means to determine the form of the vertical movements that have occurred in the forearc. The mignitude of these movements provides new constraints on thermal and mechanical models for the evolution of active margins. For example, the drill data at Site 438/439 off Japan suggest that there may be a significant mechanical component to the subsidence of the forearc region (Fig. 10). However, this drill site was located in a region of relatively low heat flow between the arc and the trench (Fig. 11). Future ocean drilling should, therefore, emphasize the side of the arc toward the Japan Sea since this region has probably been relatively unaffected by the subduction process. By comparing data of the subsidence and uplift from Site 438/439 with data obtained from the side of the arc toward the Japan Sea, it should be possible to separate thermal and mechanical effects at Site 438/439.

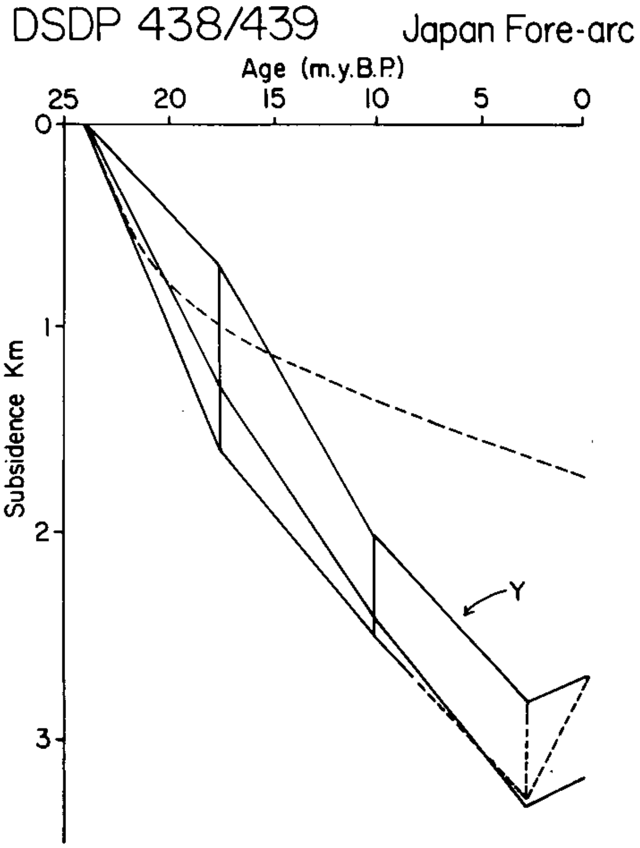


Figure 10. Tectonic subsidence at DSDP Site 438/439 (based on Langseth et al., 1981). The smooth, dashed curve represents the subsidence of a mid-ocean ridge. The subsidence in the well exceeds that of a ridge by up to 1 km.

D.4 The Stress Field at Active Margins

The stress field is probably one of the most important controls on the tectonic evolution of active margins. For example, the system of the Mariana island arc and trench is associated with an active backarc basin and an absence of large thrust-type earthquakes (Mg>8.0), while the system of the Chilean continental arc and trench is associated with absence of an active backarc basin and abundant large earthquakes. Other arc-trench systems generally show a transition between these tectonic "end members." This suggests two main modes of subduction may occur at an active margin. In one, the Chilean-type, subduction is characterized by a strong interaction between two convergent plates, while in the other, the Mariana-type, the oceanic plate is subducted without exerting any strong compressive stress on the landward plate. These basic differences in subduction modes at active margins may be the principal factor controlling differences in the topography of systems of trenches and outer rises, the type of arc volcanism, the type of metallogenesis, and the seismicity patterns in an arc-trench system.

Scientific Questions

- *What is the overall stress field across an active margin, and how does it vary along strike?*
- *What is the cause of the differences in mode of subduction at active margins?*
- *What is the relative importance to subduction of the plate angle, convergence rate, age of subducting oceanic plate, and presence or absence of an active backarc basin?*

Solutions to Scientific Questions

- Seismological studies of active margins using data from carefully selected hypocenters and focal mechanisms of large earthquakes.
- Comparative studies of the main tectonic features of active margins, such as topography of systems of trenches and outer rises, types of magma in volcanic arcs, nature of metallogenesis of arcs, and the lengths of rupture zones of large thrust-fault earthquakes between different island arc-trench systems and continental arc-trench systems.
- Deep crustal drilling combined with geological and geophysical downhole experiments, such as borehole gravimeters, tiltmeters, seismometers, hydrofracturing, and azimuthally oriented photography.

Future Ocean Drilling

Future drilling should emphasize both Mariana-type and Chilean-type active margins. Drilling should be focused in the forearc region since this region best shows the details of the subduction process (Fig. 12). However, drilling should also include the trench and outer rise and the arc and backarc basin. Downhole geological and geophysical experiments should be carried out to monitor temporal changes in seismicity, gravity, tilt, and state of stress at active margins. These experiments will be one of the most promising means in the future of determining the actual stress field at active margins.

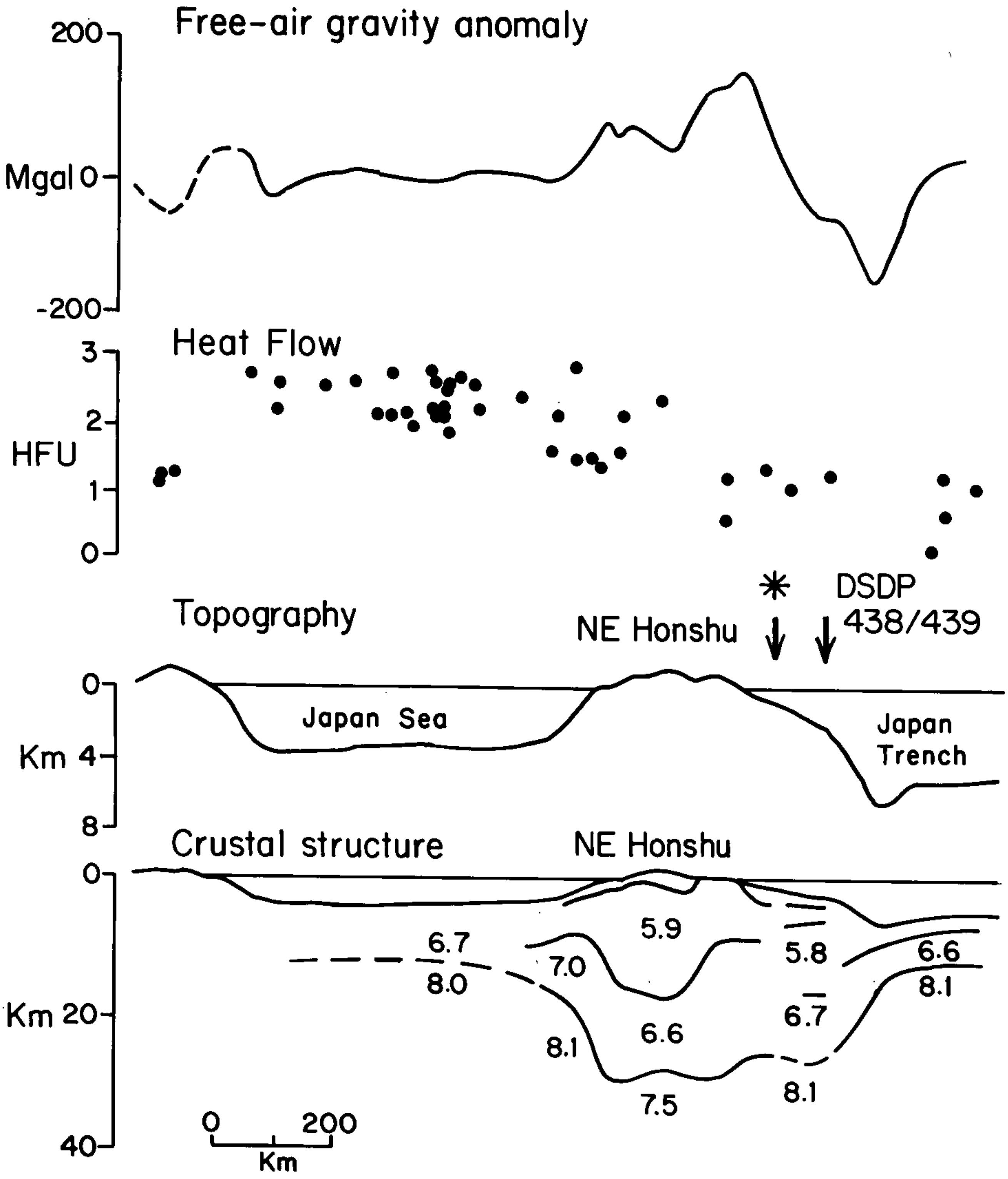


Figure 11. Crustal structure of the system of the northeast Japan island arc and trench (from Uyeda, 1977). The asterisk indicates the location of the commercial exploratory wells.

E. TECTONICS OF THE WORLD'S OCEAN BASINS AND THE ROLE OF FUTURE OCEAN DRILLING

We have outlined in this report some of the major scientific questions concerning the tectonic evolution of the oceanic crust and continental margins. These questions will require a number of different geological, geochemical, and geophysical approaches in the future in order to address them. The most important of these are:

- Seismic refraction and reflection profiling.

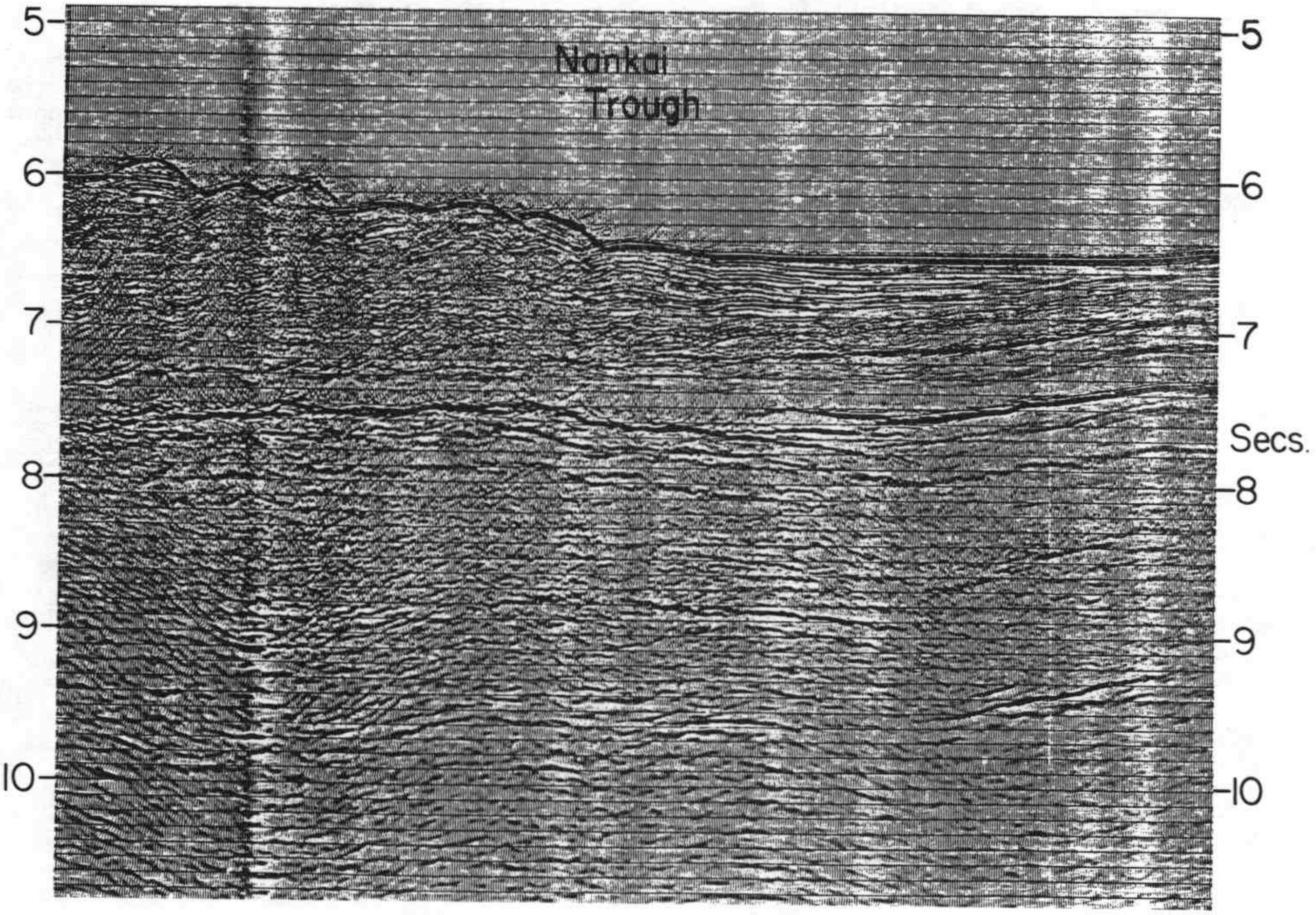


Figure 12. Seismic reflection profile of the Nankai Trough south of Japan (S. Uyeda, pers. commun.). Note the strong reflector at 9.2 to 10.0 sec that shows the top of the subducted Shikoku Basin oceanic crustal layer.

- Deep crustal drilling combined with downhole experiments.
- Manned submersibles.
- "Swath" bathymetric mapping systems.
- Towed vehicles.
- Subsidence and uplift measurements.
- Quantitative thermal and mechanical modeling.

The role of deep-ocean crustal drilling in addressing major tectonic problems in the future requires consideration of the following factors:

- There is a substantial amount of commercial and "COST-type" drilling data that already exist for continental margins, particularly in coastal plains, outer continental shelves, and upper slopes. A number of major tectonic problems at passive margins (sea level, "global" unconformities) can be addressed using these data.
- A number of tectonic problems in the oceans, such as the dynamics of magma chambers, structure of fracture zones and transform faults, oceanic plateaus and aseismic ridges, intraplate volcanism, backarc basins and forearc basins can be addressed using *Glomar Challenger-type* drilling.
- Some tectonic problems in the oceans, such as the nature of attenuated crust at passive and active margins, the depositional environment of sediments during initial rifting of passive margins, and the composition of oceanic Layer 3 and sub-oceanic mantle, will require a more enhanced drilling capability than currently available with *Glomar Challenger.*
- There are some major tectonic problems, such as the field mapping of ophiolite complexes and allochthonous terranes, the cause of long-wavelength gravity, geoid, and depth anomalies, the rheology of oceanic lithosphere; and the thermal and mechanical evolution of passive and active margins, that do not specifically require future ocean drilling.

We have not attempted in this report to specifically locate drill sites. The choice of future oceanic drill sites should, we believe, be made by groups of international, inter-disciplinary, and inter-institutional earth scientists. Since a number of tectonic problems include geological studies both of oceans and continents, this group should include scientists who traditionally work *both* in oceans and on continents.

We therefore make the following recommendations for future scientific ocean drilling:

a) That a *vigorous* program of ocean drilling using the present capabilities of the *R/V Glomar Challenger* be carried out in conjunction with other marine geological and geophysical studies in the world's ocean basins. This program should be focused to address specific tectonic problems of the dynamics of magma chambers, the origin of oceanic plateaus and aseismic ridges, intraplate oceanic volcanism, crustal structure composition, and the origin of fracture zones and transform faults.

b) That a *coordinated* program of deep crustal drilling and seismic reflection and refraction profiling be carried out at passive and active margins in both oceans and continents. This program should be focused in a number of critical *transects* of passive and active margins in order to address the problem of the origin of the vertical movements (uplift and subsidence), the nature of the control (tectonic or eustatic) on stratigraphic sequences, and the physical properties and composition of attenuated crust.

c) That deep crustal drilling in the oceans and continental margins be accompanied by an active program of downhole geological and geophysical instrumentation development and experiment.

F. REFERENCES

Detrick, R.S., Sclater, J.G., and Thiede, J., 1977, The subsidence of aseismic ridges: Earth and Planet. Sci. Letters, v. 34, p. 185-196.

Detrick, R.S., and Purdy, G.M., 1980, The crustal structure of the Kane Fracture Zone from seismic refraction studies: Jour. Geophys. Research, v. 85, p. 3759-3777.

Langseth, M.G., Von Huene, R., Nasu, N., and Okada, H., 1981, Subsidence of the Japan trench forearc region of northern Honshu: Oceanologica Acta, Spec. Issue, Proceedings of the 26th International Geological Congress, p. 173-180.

Montadert, L., de Charpal, O., Roberts, D., Guennoc, P., and Sibuet, J.C., 1979, Northeast Atlantic passive continental margins: rifting and subsidence processes, *in* Talwani, M., Hay, W., and Ryan, W., eds., Deep drilling in the Atlantic Ocean: Continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 154-186.

Mutter, J., Talwani, M., and Stoffa, P., 1982, Origin of seaward dipping reflectors in oceanic crust off the Norwegian margin by "subaerial seafloor spreading": Geology (in press).

Steckler, M.S., and Watts, A.B., 1978, Subsidence of the Atlantic-type continental margin off New York, Earth and Planet. Sci. Letters, v. 41, p. 1-13.

Uyeda, S., 1977, Some basic problems in the Trench arc — Back Arc System, *in* Talwani, M., and Pitman, W.C., III, eds., Island arcs, deep sea trenches and back-arc basins, Maurice Ewing Series, Vol. 1: Washington, D.C., American Geophysical Union, p. 1-14.

Vail, P.R., Mitchum, R.M., and Thompson, S., 1977, Seismic stratigraphy and global changes of sea level, Part 4: Global cycles of relative changes of sea level: Tulsa, Oklahoma, Amer. Assoc. Petroleum Geologists Memoir 26, p. 83-97.

Watts, A.B. and Steckler, M.S., 1979, Subsidence and eustasy of the continental margin of eastern North America, *in* Talwani, M., Hay, W., and Ryan, W., eds., Deep drilling in the Atlantic Ocean: Continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 218-234.

ORIGIN AND EVOLUTION OF MARINE SEDIMENTARY SEQUENCES

A. INTRODUCTION

This report follows a very simple organization scheme by discussing first, topics of sedimentation and the depositional environment, then sedimentary mass-balancing which implies a global view of sedimentation, and, finally, post-depositional alteration of sediments. The order of topics in this report implies no ranking by priority.

A necessary condition for the inclusion of a scientific topic here is that it requires a dynamically positioned drillship as an essential component of scientific strategy. This means that drilling in water 800 meters deep is important but does not exclude the possibility that some projects may require drilling in environments of upper slope, shelf, or even coastal plain for their complete solution. In fact, several objectives listed here require information from continental shelves and adjacent land areas. Throughout this report, we tacitly assume that this information will be available through other drilling activities such as Continental Scientific Drilling Program and COST wells. Should this not be the case, targets on continental shelves and even on land may have to be upgraded to high-priority objectives of ocean drilling.

The results to be expected from the recommended projects will be of two kinds. Some will directly bear on the history of the oceans; others will provide standards for the interpretation of the sediment record — ground truth for seismic surveys and "models" for the geologic record on land. Some objectives, such as Mesozoic rise sediments or evaporites, may require riser capabilities and deep penetration. In these areas we are still in the "wild-catting" stage, and a single hole per each objective would already yield very significant results. Most other targets are within reach of a *Glomar Challenger*-type vessel, but they almost universally require carefully designed drilling plans including many holes and detailed vertical and horizontal control. The recommendations characteristically include transects across parts of ocean basins and comparison of several oceans. Drilling on carbonate platforms requires different (and less expensive) drilling platforms altogether.

For sedimentological studies, the scientific yield per hole will be greatly enhanced by a number of relatively inexpensive devices.

1. Hydraulic piston corer to minimize disturbance.
2. Core orientation for paleomagnetic studies (including grain fabric).
3. Large-volume syringe sampling (soft formation) and rock-chunk sampling (hard formation) of cores for physical properties.
4. Velocity measurement in cores by sonic probe (soft formation) under in situ pressure conditions and by Hamilton frame velocimeter (hard formation).
5. Pressure core barrel coordinated with use of a controlled temperature-pressure chamber within which physical characteristics can be measured.
6. Dipmeter.
7. Measurement of in situ shear strength.

Seismic surveys are absolutely essential to plan and execute the recommended drilling projects. Because many objectives call for only a few hundred meters of penetration, high-resolution seismics (with frequencies in the 10^2-Hz range) is often preferable over conventional high-energy tools. Projects, such as studies of submarine fans or contourites, that attempt to relate vertical sequence to the topography of the sea floor will strongly depend on state-of-the-art bottom surveys with multi-beam sounders.

Bore-hole logging is very important, but one has to keep in mind that the tools are normally designed for holes drilled with a riser and circulation control. Open-hole drilling with a *Glomar Challenger*-type vessel is at a disadvantage in this respect.

B. SEDIMENTATION

B.1 Deep-Sea Sedimentation and Sea Level

The past decade has seen a renewed interest in the variations of sea level and their impact on the geologic record. One of the most significant developments in this field was the theory postulated by Vail et al. (1977) that the onlap of coastal sediments is directly related to the rise and fall of the sea on the continents; the coastal onlap curves are correlatable on a global scale and are, therefore, thought to contain a strong eustatic component.

The curve of global sea level by Vail et al. indicates a heirarchy of at least three orders of cycles. The first-order cycles with periods of several hundred m.y. seem to be linked to changes in the rate of seafloor spreading, and their timing matches predictions based on spreading rates (Pitman, 1978). The cause of the second- and third-order cycles documented by Vail et al. with periods of 10-80 m.y. and 1-10 m.y., respectively, remains unexplained, as does the apparent suddenness of falls of sea level in these cycles. Questions also remain about the exact timing and magnitude of the second- and third-order fluctuations of sea level (e.g., Olsson et al., 1980). Documentation of these factors is slight. Finally, the relative control of sea level on the sedimentary record in the deeper part of the continental margins and ocean basins, compared to "pelagic controls" on facies, is uncertain.

Sea Level and the Pelagic Record. A particularly puzzling facet of the curves of sea level is the apparent rapidity of the falls of sea level. If, as some have postulated, the fluctuations are related to climate and ice-volume changes throughout the Mesozoic and Cenozoic, there should be a recognizable correlation to records of oxygen isotopes. Careful selection, coring, and analysis of an optimum (composite) stratigraphic sequence for Mesozoic and Cenozoic time is an obvious test for this hypothesis. Should the hypothesis fail to be confirmed, the data may clarify controls by other mechanisms.

Sea Level and Deep-Margin Effects. The effects of the fluctuations of sea level in shallow (shelf/slope) areas of continental margins are reasonably well documented. However, no consensus exists as to areas such as continental rises and abyssal plains. Some authors postulate cyclic deposition in unison with the continental shelf (Vail et al., 1980), while others reject the notion of straightforward correlation between sea level and deep-sea stratigraphy (Tucholke, 1981; see Figs. 1, 2). This discrepancy may be

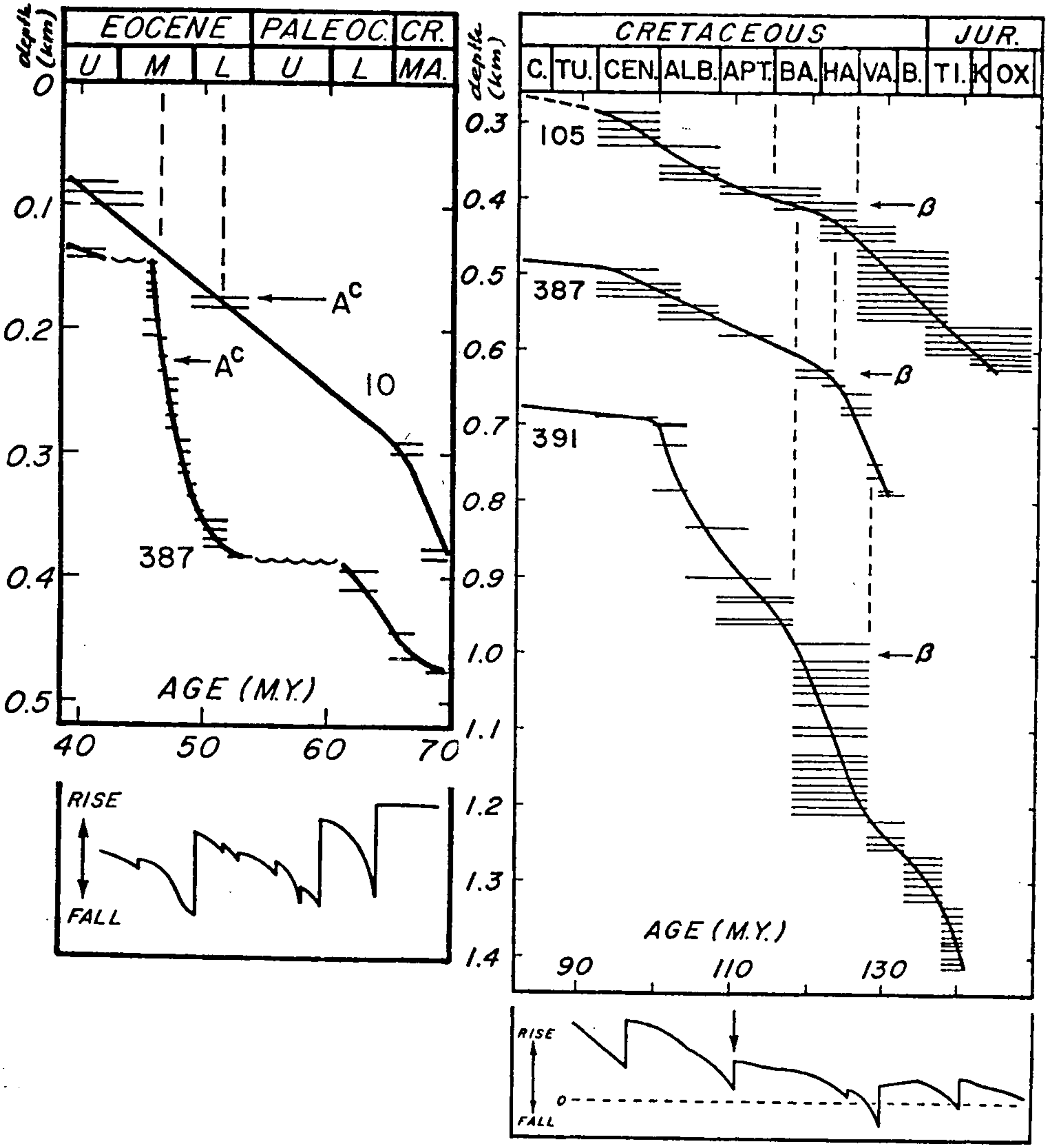


Figure 1. Curves of age versus depth-in-borehole at five DSDP sites and curve of sea level by Vail et al. (1977). Horizontal lines give biostratigraphic age ranges; wavy lines indicate hiatuses. Note the lack of coherent response of sediment accumulation to fluctuations of sea level. At Site 387, rapid sedimentation continues uninterrupted in spite of a drop in sea level at 49 m.y.; horizon beta at Sites 105, 387, and 391 (ranges shown in dashed lines) is not correlatable with any major fall in sea level (after Tucholke, 1981).

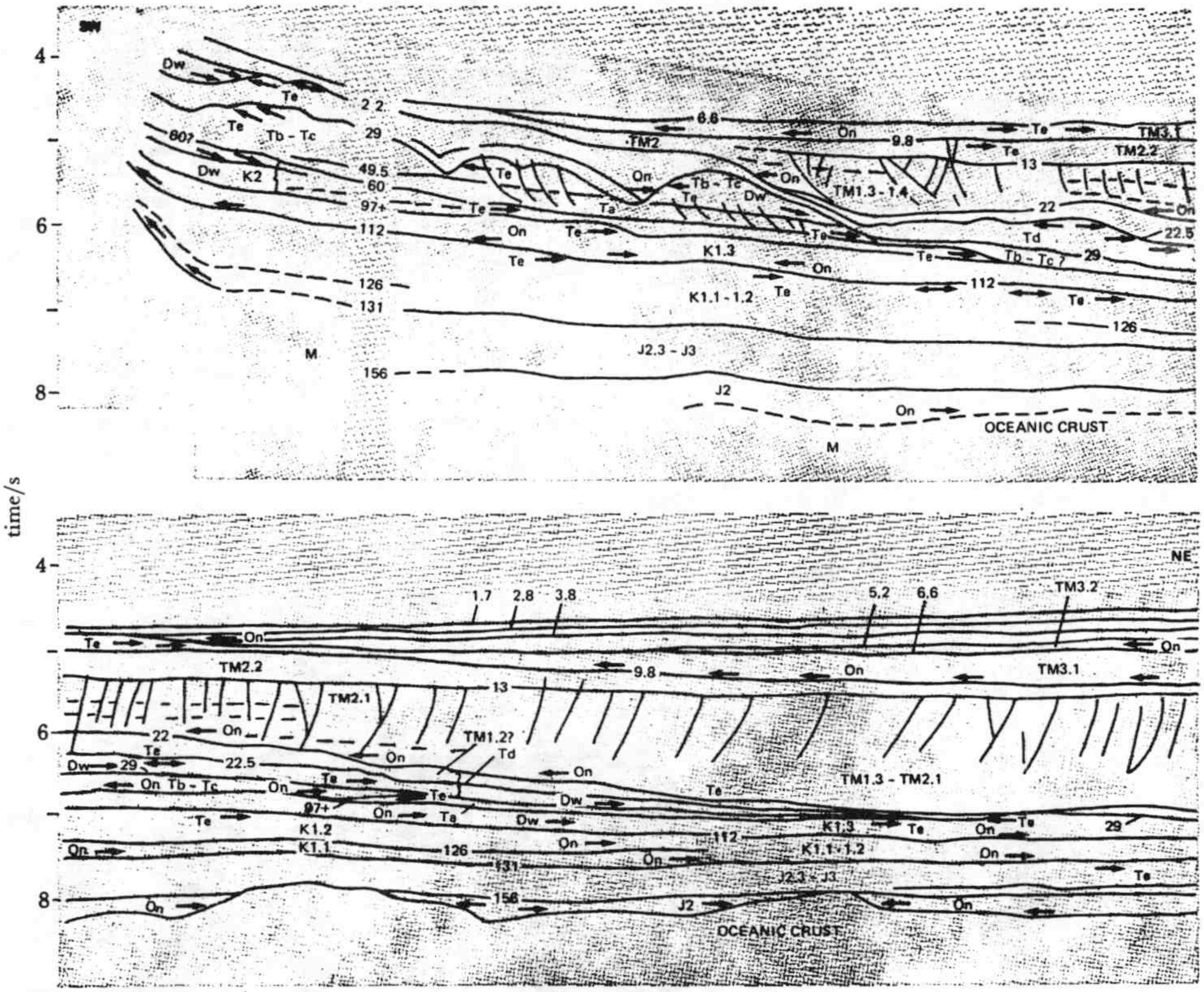


Figure 2. Seismic profile of lower continental rise, southeastern United States; 12-fold, common-depth-point stack; interpreted by Vail et al. (1980). Deep-sea unconformities shown here are claimed to correlate with low-stand unconformities on the continental shelf.

partially a result of the fact that other factors influencing the sedimentary record (e.g., abyssal currents, variations in the calcium carbonate compensation depth, productivity changes) become relatively more important offshore. It also is a result of the limited resolution of seismic stratigraphic techniques in these more slowly accumulating sedimentary sequences. Transects of boreholes across a seismically well-documented passive margin would do much to resolve the utility of predicting deep-sea stratigraphy from curves of sea level. These transects should sample margins where local tectonics, bottom-current effects, etc. can be determined or predicted, and where biostratigraphic control can be optimized. Locations should include prograding slopes, such as the north slope of the Gulf of Mexico, erosional slopes, such as off West Africa, and flanks of carbonate platforms.

Relation of Sea Level to Abyssal Currents. Some suggestions have been made in the literature that lowered sea level correlates with intensified abyssal currents and formation of hiatuses in the deep sea (Vail et al., 1980). Unfortunately, we are not certain of the mechanism to explain such a relationship, although activities of bottom circulation might be enhanced at times of more intensive glaciation. Increased sediment input, rather than hiatuses, should accompany low stands of sea level, as, for instance, during the Pleistocene low stands. However, it is possible that low stands and current intensity do correlate and are mutually controlled by a climatic mechanism. This possible correlation merits investigation. It can be studied by careful documentation of the timing of abyssal circulation events at locations where current-eroded unconformities approach conformity. This timing can then be compared with the curve of sea level as documented below.

Sea Level and the Shallow Margin. Clear documentation of the timing and magnitude of low stands can be achieved by coring at carefully selected drill sites along the continental margin. Ideal sites would have a good carbonate sedimentary record to maximize biostratigraphic control, restricted dilution by clastic terrigenous debris, and a fairly continuous sedimentary record that minimizes the duration of hiatal gaps.

One area having these characteristics is the Blake Plateau (Shipley et al., 1978; Sheridan and Enos, 1979), and it therefore may merit special attention for a drilling transect. The nearby source of clastic material during low stands (Florida, Florida shelf) is small enough that it would not swamp the sedimentary record; yet it is significant enough to be detected in drilling and seismic reflection surveys. The platform has apparently undergone relatively steady subsidence and contains a good carbonate sedimentary record. There is a complication in the form of erosion and sediment redistribution by the Gulf Stream. However, this effect can be minimized by drilling on the outer plateau where Gulf Stream effects are less significant. The transect concept, used with a high-quality seismic reflection grid, also facilitates identification and separation of Gulf Stream effects.

Catastrophic Sea-Level Events. By necessity, stratigraphers have to average rates over long time intervals (commonly on the order of 10^5 to 10^6 yr). The rates of movement of sea level commonly observed with this approach are on the order of 10^1-10^2 m/m.y. (Hancock and Kauffman, 1979). We have to remember, however, that these rates are at least in part averages over time intervals of several m.y. dictated by the limited resolving power of stratigraphy. Over short time spans, sea level may have risen or fallen at much faster rates. The glacio-eustatic Holocene rise, with rates as high as 8000 m/m.y., is a case in point. The possibility exists, however, that truly catastrophic movements of sea level have occurred in earth history and are recorded in the sediments. They would provide ideal time markers. A large asteroid impact at the Cretaceous-Tertiary boundary, for instance, can be expected to cause a world-wide tsunami with widespread erosion on the shelves and gravity-flow deposits in the deep sea (Melosh, 1981). A possible mechanism for catastrophic falls in sea level may be the flooding of depressions such as the desiccated Mediterranean. Narrow reentrants flanked by steep, carbonate platforms (Exuma Sound, Bahamas, or Catoche Tongue, Yucatan) may provide undisturbed records of the debris flows triggered by catastrophic sea-level events.

B.2 The Sedimentary Record of Abyssal Circulation

In many places of today's oceans, deep thermohaline circulation is vigorous enough to erode and redistribute a large volume of fine-grained, sea-floor sediment (Fig. 3). In other areas, abyssal currents

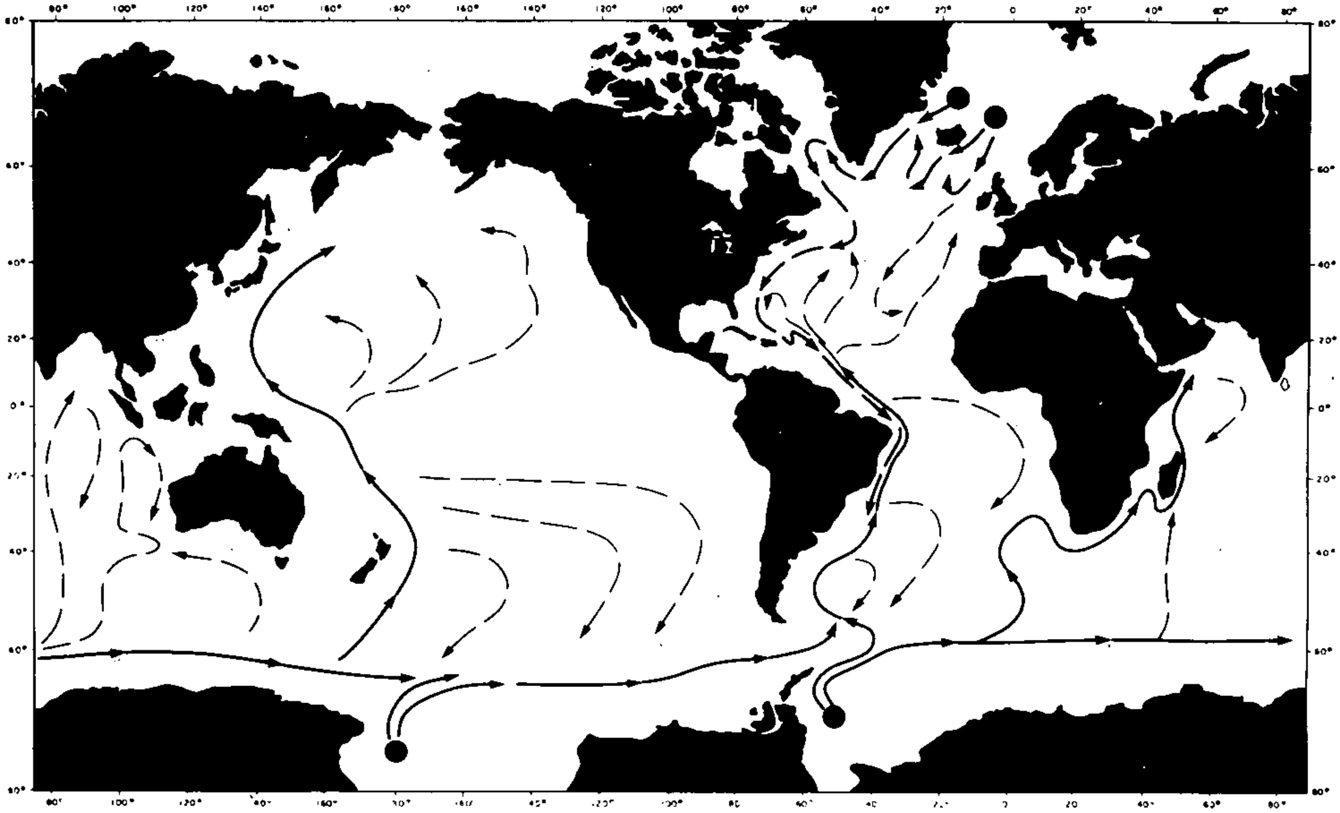


Figure 3. Deep thermohaline circulation (compiled by Stow and Lovell, 1979). Western Boundary Undercurrent shown by heavy lines; weak return flows shown by thin, dashed lines. Major sources of cold, dense waters shown as black circles. Note wide distribution of bottom currents. Western Boundary Currents and Circum-Antarctic Current have profound impact on sediment accumulations on the sea floor. The internal anatomy of these contourite deposits, as well as the history of the bottom currents, is very poorly known.

transport sediments which have probably been injected into the flow by turbidity currents or by settling of pelagic materials. These sediments are deposited wherever current speeds drop below a poorly defined threshold value for deposition. Bottom currents in most ocean basins have been identified and mapped using evidence from photographs and seismic reflection data (Heezen and Hollister, 1971). Seismic surveys coupled with deep-sea drilling have shown that bottom currents have played a major role in shaping the sedimentary record of ocean basins. Throughout the Cenozoic, significance of such currents may match or exceed that of turbidity currents. The vestiges of these currents are erosional unconformities and sediment accumulations ("contourites") ranging in size from ripples to giant ridges that are thousands of meters high and tens of thousands of square kilometers in size.

Contourites and associated erosional unconformities represent the best record of deep-sea currents. However, because of discontinuous coring, mixing of the sedimentary record by rotary drilling, and poor site placement (relative to resolving abyssal circulation history), we still have only the vaguest notion of the relative timing and magnitude of abyssal-current events in the major ocean basins.

A programmatic approach to solving some of these problems should be based on several guiding principles:

1. High-resolution seismic surveys including regional tie lines and site-specific grids are an absolute pre-requisite to proper site placement and subsequent interpretation of borehole results. The interpretation would be strongly aided by borehole logging.
2. Insofar as possible, primary drill sites should be situated to sample significant unconformities at the location where they become conformities. These may, and in many cases should, be supplemented by nearby drill sites that sample the unconformities where they are well developed.
3. As a first step, the program should concentrate on areas where there are known to be coherent, basin-wide responses of the sedimentary record to major circulation events. While there are numerous local or even quasi-regional patterns of current-controlled sedimentation, these are of subsidiary importance to documenting precisely the major events.

We need to drill contourite sequences for several reasons: (1) to examine the geometry of these accumulations in three dimensions in order to understand the interplay of currents and topography in shaping the depositional record, (2) to test the criteria for contourite recognition at the "hand-sample" scale, and (3) to document the history of circulation of bottom water. In this regard there may be significant differences between the Cenozoic temperature-dominated circulation and, say, the Cretaceous circulation which could have been driven largely by salinity gradients.

Contourite Drifts. The most spectacular products of contour-current deposition are ridge-like piles of sediment that can be many hundreds of kilometers long and over a thousand meters high. They consist mainly of silt and clay, and they exhibit a variety of bedforms. Typical examples of contourite drifts are the Blake, Bahama, Caicos and Antilles outer ridges in the western North Atlantic or the Eirik and Gardar drifts in the northern North Atlantic.

The Blake Outer Ridge, covered by an extensive grid of seismic lines and drilled at DSDP sites 102, 103, 104 and 533, is probably the best known of these features. Yet even there, drilling has only "scratched the surface" of this huge feature (Fig. 4, Hollister, Ewing et al., 1972; Gradstein, Sheridan et al., 1981). Drilling has gone far enough, however, to show that the lens-shaped packages of hemipelagic sediment were deposited at rates as high as 190 mm/1000 yr, and that homogeneous muds (probably deposited from nepheloid layers), as well as laminated silts and sands (traction-current deposits), are present (Stow and Lovell, 1979). Seismic reflection profiles show that the Blake Outer Ridge has a complex internal geometry and a "multiphase" evolution. They also suggest that the adjacent Bahama Outer Ridge is a late-phase addition to the Blake-Bahama System. Such apparent large-scale geometric relations need to be thoroughly documented by appropriate seismic reflection surveys and then tested by drilling. The drilling will relate both large- and small-scale contourite characteristics to the abyssal circulation history.

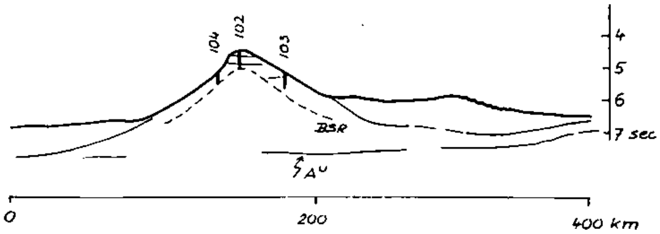


Figure 4. Cross-section of Blake Outer Ridge (after Hollister, Ewing et al., 1972) showing approximate penetration of DSDP holes. Blake Outer Ridge is the best-documented contourite drift, but even there only a small portion of the total sediment pile has been penetrated. Reflector A^u underlying the ridge marks major erosional pulse in the Oligocene.

Mud Waves. Mud waves have been described both from deep-water settings (submarine fans, continental rises) and from shelf environments (Normark et al., 1980). They have been identified from echograms, side-scan sonar surveys, and seismic reflection surveys only. The following problems regarding mud waves can best be resolved by drilling:

1. What is the nature of the sediments with respect to texture, grain size, internal sedimentary structures, and vertical sequences?
2. What process(es) forms the mud waves?
3. What is the age of the mud waves? Are they static features, relicts from an earlier depositional regime, or are they actively forming today?

Contourites (Hand-Sample Size). "Contourites" from along continental rises, where it is difficult to separate out the effects of turbidity currents, have been studied from a variety of piston cores (e.g., Stow and Lovell, 1979) and other sampling devices. On sedimentary outer ridges where the sea floor is isolated from turbidity currents and deposition is *only* from bottom currents, contourites have not been properly cored or studied. Judiciously placed hydraulic piston core drill sites would help define the textural variations that can be attributed to "contourites" and would document the relation of these variations to variations in abyssal circulation history.

Unconformities. A great deal of information can be derived from study of gaps, or hiatuses, in the sedimentary record. Hiatuses record a change in the balance between sediment supply and removal processes. Although spanning virtually all time intervals, studies have documented the apparent increase in the incidence of deep-sea hiatuses at certain times in the past (Fischer and Arthur, 1977; Moore et al., 1978). Because most widespread hiatuses are thought to be confined to relatively short (i.e., 5 m.y.) intervals of time, and because they are thought to be due largely to erosional events caused by enhanced circulation of bottom currents, they are sometimes used as stratigraphic markers bounding depositional sequences. They characteristically have a seismic signature and, therefore, are used for seismic correlation (Tucholke and Mountain, 1979; Vail et al., 1980). However, the age and lateral extent of such hiatuses have not been precisely documented. In most cases we do not know the origin of deep-sea unconformities — whether they are due to cessation of supply of sediment, to current erosion, or to increased rates of dissolution at depth. Rarely have we recovered a "hiatus" in cores to study. In conjunction with biostratigraphic studies, detailed sedimentological, geochemical, and mineralogical studies of one or more major hiatal surfaces should be undertaken in order to estimate the relative effects of current erosion and/or dissolution. Obviously, sediment supply factors and studies of sediment redistribution by deep currents are integral parts of the documentation of hiatuses and their origin. In fact, it seems a paradox that a major widespread late Eocene-Oligocene hiatus (horizon A^u; Tucholke and Mountain, 1979) in the deep sea appears to coincide with lowered sea levels and low rates of accumulation of shelf sediments; this is a time when major sediment flux to the deep sea would be expected. Apparently, the hiatus resulted from enhanced erosion by intensified bottom currents, but the problem of sediment budget is unresolved. It remains uncertain whether the drop in sea level and the erosion event are indeed synchronous.

It is important, therefore, to understand the origin of submarine unconformities, particularly if they are to be used as time-stratigraphic horizons. We propose documentation of at least one major hiatus in several basins. Again, the Eocene-Oligocene event may provide the most accessible example, and detailed drilling of this type will interface well with other research proposed here.

We recommend that drill sites be located to sample the hiatus at its maximum and minimum extent (correlative conformity), as well as at several closely-spaced sites along several transects in order to ascertain the age of the erosion/dissolution event that caused the hiatus. The hiatus itself should be cored in order to provide adequate dating and chemical-sedimentological (textural) studies.

The retreating flanks of carbonate platforms in the western Atlantic are a special type of hiatus that may be linked to current erosion (Paull and Dillon, 1980; Freeman-Lynde et al, 1981). Hundreds of cubic kilometers of hard limestone have been removed along the track of the Western Boundary Undercurrent, and the mechanism of erosion is essentially unknown. Drilling into the sediment accumulations at the foot of these escarpments could do much to elucidate this startling phenomenon.

History of Abyssal Circulation. The most important question to be settled through a study of contourites and unconformities is the Cenozoic history of circulation of deep water with its northern and southern sources. Further down the road, these studies will inevitably lead to the infinitely more difficult question of bottom circulation in the Cretaceous and older oceans.

Northern Sources of Deep Water. The northern and western North Atlantic Ocean basins are well known to have been affected by circulation of bottom waters originating in the Labrador and Norwegian-Greenland seas. However, the nature and timing of formation of bottom water at high latitudes remains uncertain. At some point between late Eocene and early Miocene time, very strong abyssal circulation eroded a major unconformity along the continental rise of eastern North America. This was followed by strongly current-controlled deposition in the early to middle Miocene in both the northern and western North Atlantic and perhaps by another widespread late Pliocene erosional pulse.

The exact timing and nature of these circulation events should be studied by judicious, continuous hydraulic piston coring. Applicable analyses include, but are not limited to, biostratigraphy, oxygen- and carbon-isotope stratigraphy of planktonic and benthonic foraminifera, paleomagnetic stratigraphy and magnetic grain orientation, geochemical stratigraphy, and lithostratigraphy. These are intended to resolve the timing, temperature, and salinity influences (paleocirculation/paleoclimatic) and the effects of "tectonic topographic thresholds" on circulation of bottom water.

Possible sites to study include the following:

1. Feni Ridge, Gardar Drift, Eirik Ridge, Gloria Drift, Southeast Newfoundland Ridge, Hatteras Outer Ridge, Bahama Outer Ridge, Caicos Outer Ridge, Antilles Outer Ridge.
2. Seaward edge of Horizon A^u unconformity (near-conformity) — Nova Scotian rise-abyssal plain contact, northwesternmost Bermuda Rise, seaward edge Caicos Outer Ridge.
3. Northern Bermuda Rise (unusually thick Neogene sediments).
4. Transects across a well-developed, typical sediment wave (e.g., Bahama Outer Ridge).

Southern Sources of Deep Water ("Atlantic Sector"). Modern flow of Antarctic Bottom Water strongly affects sedimentation in the Argentine Basin and farther north in the Cape and Mozambique basins.

In general, bottom water originating from high-latitude, southern sources has had profound effects on sedimentation in these areas (unconformities, sediment waves, etc.) at least since the Oligocene and perhaps as early as Paleocene/Eocene time. The timing and nature of formation of these bottom waters (and their potential resemblance to modern Antarctic Bottom Water) are no better understood than their northern counterparts.

Recent results from Leg 72 of the Deep-Sea Drilling Project (Barker, Carlson, Johnson et al., 1981) indicate pulses of erosion in the South Atlantic, possibly caused by repeated invasions of Antarctic Bottom Water. To date, the variations of bottom-water circulation have been documented at a few points, but we are far from a comprehensive regional picture.

The history of abyssal circulation in these regions can be fruitfully studied in several generic areas by following the same rationale as outlined for paleoclimatic and threshold-tectonic events in the North Atlantic.

Possible sites to study include the following:

1. Argentine Basin sediment waves.
2. Agulhas Plateau — four-hole transect from 3000 to 4500 meters.
3. Mozambique Basin sediment waves.

Southern Sources of Deep Water ("Pacific Sector"). Drilling here can be expected to address the timing of advection of circumpolar water eastward into the Pacific, the cessation of northward flow along western Australia, the entrance of Antarctic Bottom Water into the southern Pacific and the development of a Western Boundary Current there, and the entrance of Antarctic Bottom Water into the eastern equatorial and the northeastern Pacific.

All these relate both to "tectonic threshold" effects and to possible bottom-water production in the Ross and Weddell seas caused by both "high-frequency" and longer-term paleoclimatic events. These generic drilling areas should be supplemented south of the Pacific-Antarctic Ridge by sites drilled into current-controlled drift deposits and unconformities. Such features are as yet poorly documented in existing seismic reflection data. The relative timing of events north and south of the Pacific-Antarctic Ridge will give an indication of the "threshold" effects of the ridge.

Possible sites to study include the following:

1. Campbell Plateau/Chatham Rise, Macquarie-Balleny Ridge.
2. Exmouth Plateau, Naturaliste Ridge.
3. Northern exit Samoan Passage, northern exit Wake Island Passage, drift deposits at Aleutian-Kamchatka junction, transect on the eastern flank of Ontong/Java Plateau.
4. Eastern exits of Horizon Passage, Clarion Passage, etc.

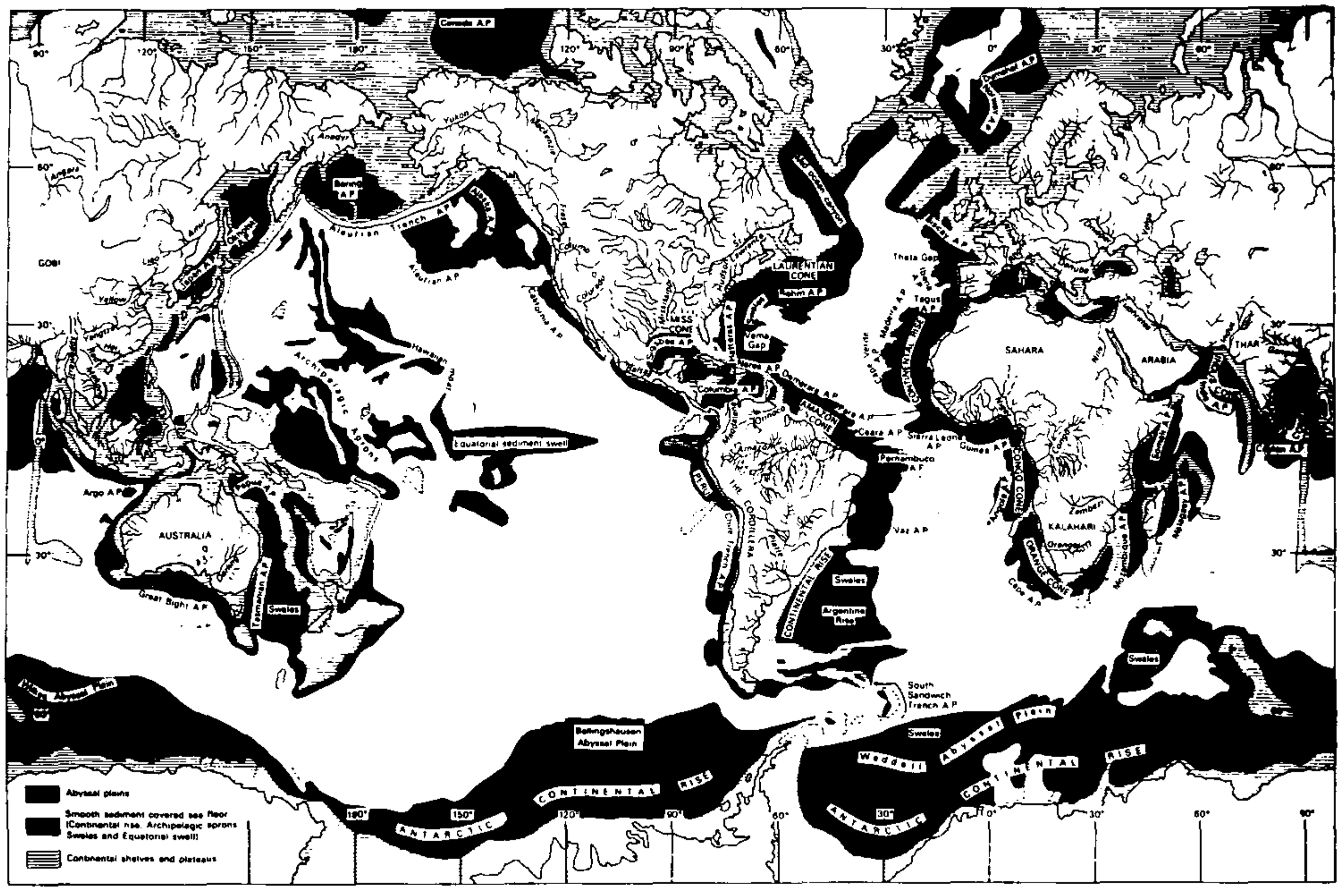


Figure 5. World distribution of major deep-basin plains, abyssal cones, and rises all shown in black (from Heezen and Hollister, 1971). Abyssal cones are generally made up of deep-sea fans. The vast majority of them have not been explored by the drill, and the facies models on fans urgently need three-dimensional well control. Likewise, deposits of contour currents on the rises have hardly been drilled although they hold the key to the history of bottom circulation in the world ocean.

B.3 Gravity-Displaced Sediments

Submarine Fans. We have learned in the past decades that deep-sea fans composed of turbidites and related deposits are a common element in ocean basins and occur in a variety of settings, including both active and passive ocean margins (see Stanley and Kelling, 1978; Rupke, 1978; Fig. 5). In modern oceans, these fans have been studied by a combination of bottom surveys and sampling programs that revealed morphologic features and facies patterns from several kilometers upward in scale (Shepard and Dill, 1966; Normark, 1970; Nelson et al., 1970). In the geologic record, too, facies and geometry of deposits of gravity flows were used very successfully to subdivide fan complexes. There, however, geometry was defined in outcrops revealing features on a ten- or hundred-meter scale (Mutti and Ricci-Lucchi, 1978; Walker, 1976). Furthermore, modern fans are recognized by their topography and their horizontal facies patterns, while ancient fans are identified mainly by the vertical succession of facies. The correlation of these facies with topographic features on a fan (for instance, Fig. 6) is well thought out but remains hypothetical. Of modern fans, on the other hand, we lack the knowledge of their vertical sequence in spite of excellent morphologic and seismic studies (Normark, 1970; Nelson, 1976). Because of this mismatch in the kind of data, we are currently unable to determine if ancient and modern fan models are different because they are based on different types of information or because of a difference in settings (see Nilsen et al., 1980).

Like deltas, deep-sea fans are a family with rather diverse members. For deltas, it has been shown that their shape and facies patterns result from the interplay of sediment discharge by the river and marine forces such as wave energy (Wright and Coleman, 1973). For deep-sea fans we do not have such a unifying concept, but one may well emerge from an organized drilling campaign.

At present we recognize a minimum of six types of deep-sea fans based on overall setting and sand/clay ratios:

1. Giant and large fans (Indus, Bengal, Amazon, Mississippi, Laurentian?) in wide ocean basins. Many are fed via mud-rich deltas and therefore have a low sand/clay ratio.
2. Medium and small fans (Rhone, Ebro, Monterey, Astoria, Delgado, Navy) with high sand/clay ratios. These are often not directly fed via deltas and are deposited in small sub-basins off mountainous coasts.
3. Migrating channel fans (Cap Ferret) with a major channel that migrates to one direction under the influence of tectonics.
4. Fans in elongate basins of tectonic origin, primarily trenches.
5. Fans in trench-slope basins.
6. Fans in high latitudes off fjords.

Drilling into modern fans with well-documented surface patterns provides the only opportunity to see the geometry of a submarine fan in all dimensions and to close the gap between studies of modern and ancient fans. We also have reason to believe that submarine fans, like deltas, can be described by well-defined facies models that will serve as predictive tools in the search for porous sands, stratigraphic traps, and hydrocarbon source beds in deep-water environments.

Drilling strategy for deep-sea fans should be guided by the following considerations. Drilling must cover the main topographic elements, such as fan channels, levees, mid-fan lobes, proximal and distal interchannel areas, and fan margins. Penetration can be limited to a few hundred meters because ancient sequences show that fan deposits characteristically consist of cyclothems normally not over 200 meters thick. One or two holes, however, should penetrate the complete fan sequence to document the response of fan sedimentation to changes in sea level and source area on a time scale of millions of years.

Drilling of deep sea fans should definitely be preceded by high-quality bottom surveys (for instance, with GLORIA, SEABEAM, or SEAMARK) and by high-frequency seismics with resolution of 10 meters or better in the upper 500 meters of sediment column. "Supersparker," "Fairflex," and to a lesser degree "Flexichoc" are examples of such systems. Fan drilling will also greatly benefit by deep-towed side-scan sonar surveys and by vibracoring capabilities.

The first drilling targets should be a small, well-documented fan in moderate water depth, such as the Monterey or Astoria fan off western North America, and a large fan, such as the Amazon or Mississippi fan. Such a program would, among other things, test the distinction between "efficient fans" with well-developed channel systems that carry sand far into the outer fans, and "poorly efficient fans" with short channel systems and most sand deposited as lobes in the middle fan (Nilsen et al., 1980, p. 1097 and 1105). A third drilling target should be a small, elongate basin where turbidity currents are confined and deflected into a longitudinal direction before they wane. The facies patterns of narrow, elongate basins show a marginal belt of small fans and often ponded turbidites with strong longitudinal transport in the center. Examples of this type of basin include such diverse settings as deep-sea trenches, basins in the California borderland, and troughs between the Bahama platforms.

A major question that can only be answered by drilling is the response of turbidity-current sedimentation to fluctuations of sea level with periods of several millions of years or longer. From the Quaternary we know that sediment input by turbidity currents is high during low stands of sea level when rivers discharge their load on or near the shelf edge. As the rising sea floods the shelf, sediment is trapped in the estuaries and coastal plain, and turbidite sedimentation in the ocean basin decreases. Does this rule hold for fluctuations with a much longer period? If so, how is this recorded in the horizontal and vertical facies patterns?

Another poorly understood process is the interplay of turbidity currents and contour currents, particularly in the outer, fine-grained portions of fans. The best opportunity to pursue this question is probably in the western North Atlantic, where fans are strongly modified by contour currents (e.g., Stow, 1981), and where large canyon systems, such as the Providence Channels in the Bahamas, discharge but are unable to

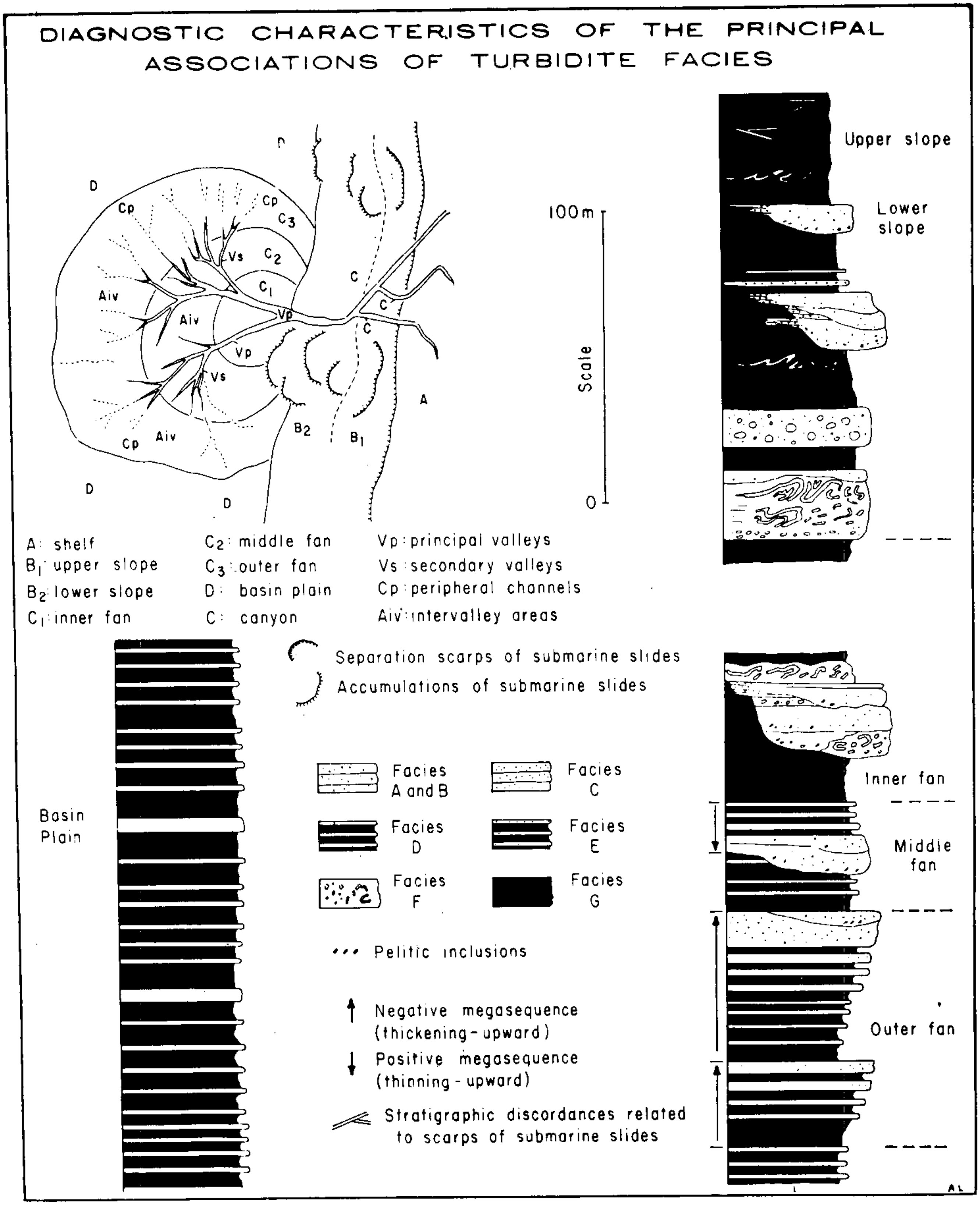


Figure 6. Environmental model and stratigraphic sections representative of the principal associations of turbidite facies (after Mutti and Ricchi-Lucchi, 1978). The correlation of ancient fan sequences with topographic features of modern fans is well thought out but remains hypothetical unless documented by drilling.

build large fans because of the effect of contour currents.

Finally, studies of fans will have to consider also the "inter-canyon areas" where, for lack of major point sources, no big fans develop.

Sandstone diagenesis should be an important auxiliary project in any fan drilling because of its significance for the hydrocarbon potential of fans. Seismic surveys indicate a variety of potential petroleum reservoirs and stratigraphic traps in submarine fans (e.g., Wilde et al., 1980). We also know that porous clean sand is deposited in many parts of a fan province (e.g., McLean, 1981). We know very little, however, about the diagenetic history of the sand bodies, in particular the interplay of compaction and cementation.

Organic matter, its provenance, deposition, and diagenesis in a fan, is another important auxiliary project in fan studies. Rapid deposition of fine sediments and high supply of terrestrial organic matter, often coupled with high concentration of marine components in zones of near-coastal upwelling, create a very favorable environment for preservation of organic matter and influence the hydrocarbon potential of fans.

Submarine Slides, Slumps, and Debris Flows. Sediment slumps are common deposits in deep-water sequences throughout the geologic record. In modern oceans, too, a growing body of literature in the past decade has demonstrated that mass-wasting by creep, sliding, and slumping is a common process on continental margins and island slopes. Dott (1963) first emphasized that slides, slumps, debris flows, and turbidity currents represent a continuous spectrum of deposits, and that the boundaries between these sediment types are determined by mechanical properties such as the elastic, plastic, and liquid limit of the material.

The anatomy of individual turbidite beds has been studied extensively by piston coring. Many modern slides, slumps, and debris flows are normally too thick to be sampled by this inexpensive technique. Consequently, their geometry and internal structure is largely unknown, and what little we do know is based on interpretation of seismic profiles badly in need of ground truth. We propose to examine large slumps in selected areas of continental margins through drilling and hydraulic piston coring. These drilling campaigns must be preceded by high-quality bottom surveys (SEABEAM, deep-towed sonars) and high-resolution seismic profiling. In several of the proposed areas these surveys are already available.

Drilling of modern slumps and large debris flows should provide the following results:

1. Detailed insight into the geometry and structure of an important sediment type.
2. An understanding of the conditions that lead to sediment failure through (mainly in situ) measurements of physical properties of stable, metastable, and slide deposits.
3. A record of slope processes as it is contained in slumps and debris flows on the adjacent continental rise in response to fluctuations in sea level and other variables.
4. Predictive models for slope failure to aid in planning and execution of offshore drilling.

Below we list some large slump deposits that are documented well enough (seismics, shallow piston cores) to adequately define their geometry.

1. United States margin seaward of New Jersey (McGregor and Bennett, 1979).
2. Eastern Mediterranean (Almagor and Garfunkel, 1979).
3. Gulf of Alaska (Carlson and Molnia, 1977).
4. Continental Borderland of California (Field and Edwards, 1980).

B.4 Sedimentation in Oxygen-Deficient Oceans

Geochemical Indicators of Organic Matter Preservation. Studies of the origin and evolution of sedimentary sequences have been made mainly on the mineral fraction of the sediments. However, the organic fraction can provide important information on the origin of the material, the alteration during transport and deposition, and the subsequent diagenetic changes.

The nature of the organic matter present in sediments can be determined by microscopy, chemical analysis, and stable isotope composition. In particular, it is possible to assess the rates and types of supply of marine versus terrestrial organic matter (Fig. 7). Furthermore, biological markers (fossil molecules) may provide information on the specific groups of organisms, either planktonic or benthic (bacteria).

These data can contribute to solve many problems, such as the importance of pelagic versus terrestrial input in turbidites or the evaluation of the ancient planktonic activity, particularly the location of upwelling areas. In deep oceanic conditions, where skeletons are not preserved below the calcium carbonate compensation depth, the organic fraction may provide a clue to planktonic productivity. For further topics, see Appendix I.

Transects of Modern Oxygen-Minimum Zones and Their Neogene Record. Preservation of organic carbon in marine sediment is a function of (1) the productivity of the overlying water column, (2) the depth of the sea floor and the degree of oxygenation of the overlying water column, and (3) the rate of sediment accumulation. High rates of primary productivity, low concentrations of oxygen in water masses impinging on the ocean floor, and high rates of sedimentation enhance the amount and degree of preservation of organic matter (e.g., Müller and Suess, 1979; Demaison and Moore, 1980). Ancient sediments rich in organic matter have been explained by various combinations of the above arguments. A model commonly applied to basin black shales is that of the silled, anoxic (euxinic) basin, which has a modern analogue in the Black Sea (top of Fig. 8). However, more recently, the concept of expanded and intensified oxygen-minimum zones impinging upon outer shelves and slopes and occasionally expanding to encounter the deeper sea floor has been applied to Cretaceous black shales in the Atlantic, Pacific, and Indian oceans (e.g., Schlanger and Jenkyns, 1976; Fischer and Arthur, 1977; Thiede and van Andel,

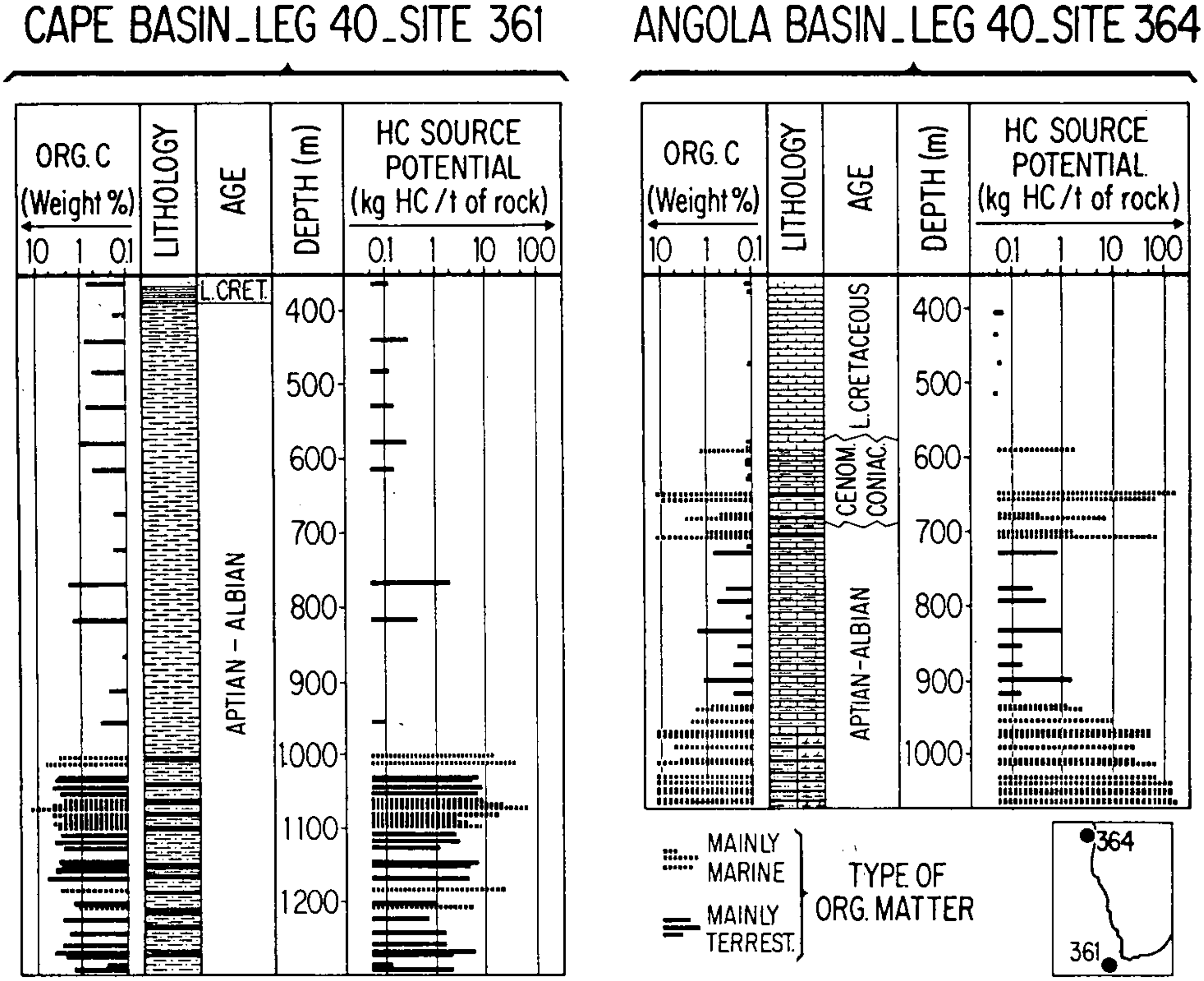


Figure 7. Geochemical well logs of Sites 361 (Cape Basin) and 364 (Angola Basin) showing organic carbon content and hydrocarbon source potential obtained from Rock-Eval pyrolysis (t=metric ton): Variations in amount and type of organic matter as recorded here may provide clues to the causes of oceanic anoxic events (after Tissot et al., 1980).

1977). In modern, well-developed oxygen-minimum zones (bottom of Fig. 8), such as occur under upwelling zones along the west-facing slopes of continental margins in trade wind belts, organic matter content is high in laminated, diatomaceous muds, particularly where dissolved oxygen content drops below 0.5 ml/l. The development and maintenance of such intense oxygen minima are the result of a playoff between productivity and circulation.

Although we know the modern setting reasonably well, we have little idea about the variation through time of surface productivity, oxygen deficits, and resulting shelf-slope sedimentary facies. *Glomar Challenger* is scheduled to drill a transect in Cenozoic sediments across the oxygen-minimum zone off Peru. We recommend drilling other transects off southwestern Africa and southern Arabia where relatively well-preserved carbonate plankton provides better stratigraphy than off Peru. These drilling transects will provide us with a comprehensive facies model which can be used to test the hypothesis of "fossil" oxygen-minimum zones on examples such as the Permian Phosphoria Formation of North America or the Cretaceous margins of western Australia or northwestern Africa.

The Mediterranean and Red Seas as Analogues to Eocene and Cretaceous Oceans. Deep circulation and the distribution of sediment (particulate organic-matter and carbonate) were undoubtedly very different in the Cretaceous oceans than they are at present. It has been proposed that, in the absence of very cold, high-latitude water masses, certain sources of warm but dense saline water derived from low-latitude shelves or restricted evaporitic basins would furnish bottom water to the world ocean (e.g., Thierstein and Berger, 1978; Brass et al., in press; Arthur and Natland, 1979). The type of deep circulation would possibly lead to increased deep-water residence times and a reduction of initial oxygen and CO^2 contents.

Indeed, during times such as the Paleocene-Eocene and the Early Cretaceous, commonly envisioned as periods of warm, saline bottom water, relatively more organic carbon was buried in the deep sea, as well as on some shelves and in epicontinental seas (see

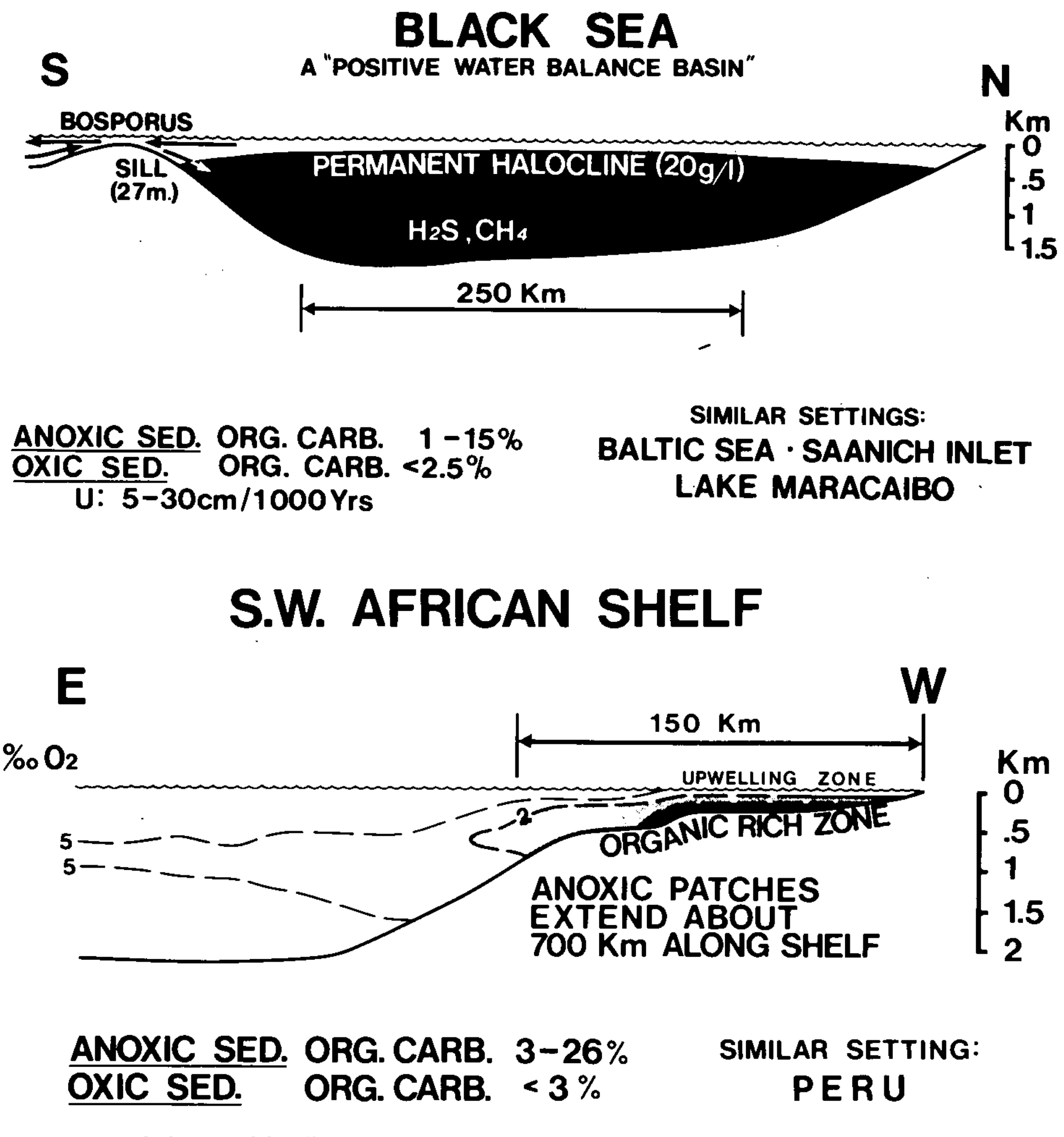


Figure 8. Top — Black Sea model: Silled anoxic basin. Bottom — Oxygen-minimum zone impinging on slope and outer shelf off southwestern Africa (modified from Demaison and Moore, 1980).

Jenkyns, 1980; Arthur and Jenkyns, 1981). Enhanced preservation of organic matter was undoubtedly due to more widespread oxygen deficits in the intermediate and deep-water masses, but it is, as yet, difficult to separate the relative effects of increased fertility and productivity and impact of terrigenous organic matter from changes in deep circulation (see the following section on **Cretaceous "Anoxic Events"**).

In order to understand the patterns of circulation and the impact of water-mass properties on bottom sediments, we need a modern analogue where all parameters could be measured. Although much smaller in scale, the Quaternary Mediterranean and Red seas are probably the best analogues to global anoxic events in the past since their circulation of deep water is typified by sinking of evaporated warm, saline surface waters and low surface productivity. Therefore, the history and the patterns of organic matter and carbonate preservation in the deepest areas of the Mediterranean and Red seas should be studied in more detail. Carbonate preservation, studies of stable isotopes, and studies of the rates of accumulation and the composition of organic matter will be useful for comparison with similar studies of Eocene and Cretaceous deep-sea basins.

Cretaceous "Anoxic Events." Study of Lower and middle Cretaceous sedimentary sequences on land and those from Cretaceous deep-ocean basins recovered in DSDP sites has led to the suggestion that during certain periods, widespread oxygen deficits occurred in all ocean basins. These so-called "Oceanic Anoxic Events" (OAE's; see Schlanger and Jenkyns, 1976; Ryan and Cita, 1977; Arthur and Schlanger, 1979; Jenkyns, 1980) occurred during the Aptian-Albian, at the Cenomanian-Turonian boundary, and to a lesser extent, in the Coniacian-Santonian. OAE's generally occurred during major marine transgressions and led to world-wide burial of large amounts of organic matter in both shallow seas and the deep sea. These events are recorded in the ratios of carbon isotopes of pelagic carbonates (Fig. 9; Scholle and Arthur, 1980). However, each of the "anoxic" episodes differs from the others and appears to have somewhat different expressions in each ocean basin. The Aptian-Albian OAE encompasses some 10 to 15 m.y., while the Cenomanian-Turonian OAE lasted probably less than 2 m.y. The former is hypothesized to have been expressed largely in a massive influx of terrestrial plant material to the northern North Atlantic-Bay of Biscay (de Graciansky et al., 1979; Habib, 1979; Arthur, 1979), in expansion of oxygen-minimum zones and increased preservation of marine organic matter in the Pacific (Schlanger and Jenkyns, 1976) and Indian oceans (Roth, 1978), and in periodic total anoxia in parts of the North and South Atlantic (e.g., Arthur and Natland, 1979; Tissot et al., 1974, 1980). The Cenomanian-Turonian OAE appears to reflect the expansion of a mid-water oxygen-minimum zone with increased marine productivity.

Despite the great interest in these Cretaceous deposits rich in organic matter, there are still a number of important problems to be solved. We need continuous coring of these deposits, minimizing drilling disturbance, in a multi-site transect across a continental margin in the North Atlantic in order to examine a time series of the changes in content and type of organic matter during an OAE (to see if, indeed, the conditions of preservation were due to anoxia) from shelf to basin. This drilling would help to determine

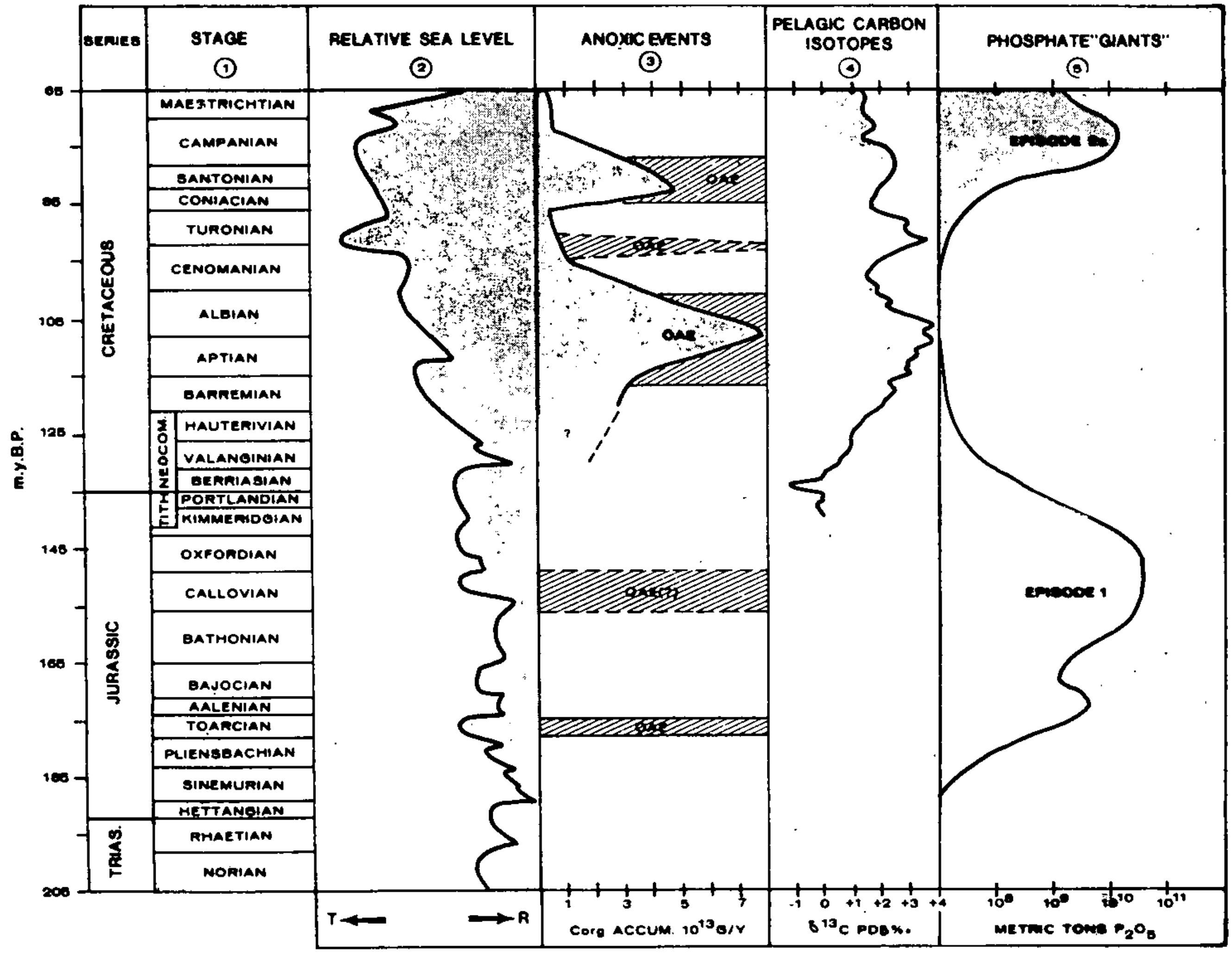


Figure 9. Relative changes of sea level, timing of anoxic events, and rate of accumulation of organic carbon in the late Mesozoic ocean basins (see Arthur and Jenkyns, 1981).

possible expansions or contractions in the oxygen-minimum zone, the depths of its influence, and whether the possible salinity stratification induced anoxia throughout the deeper parts of the Atlantic. Similar transects across a low-paleolatitudinal oceanic rise in the Pacific and across the western Australian continental margin would help delineate the timing of purported correlative OAE's, the mechanisms of preservation of organic matter, and the amount and type of organic matter preserved. Transects across ocean margins are likely to answer also the question of increased coastal upwelling in the Cretaceous. If indeed monsoons were more important then than today and provided the main mechanism for poleward transport of moisture (Manabe and Wetherald, 1980), evidence for these monsoonal systems should be found in the form of widespread zones of coastal upwelling and concomitant high plankton productivity. Silica content and abundance and type of organic matter can be used as indicators of these upwelling zones (Brass et al., in press).

The successful study of so-called OAE's requires cooperation between biostratigraphers, sedimentologists, and organic and inorganic geochemists. Establishing the age of each episode and the variations in organic content within it is a critical task. The organic geochemists will have to establish firmly the degree of preservation and source of organic matter in detail throughout a sequence, not just at a few levels. The short-term (i.e., 10^4-10^5 yr), quasi-cyclic fluctuations (Fig. 10) in organic carbon, carbonate content and accompanying faunas, sedimentological features, and geochemical changes should be the object of study since these rhythms may provide clues to the controls on structure of the water mass and preservation of organic matter (Weissert et al., 1979; see also Section B.7). Sedimentologists must carefully observe sedimentary structures in black shale sequences because much of the organic-rich intervals in deep basins may have been redeposited from organic-rich sequences in the oxygen-minimum zones on slopes (e.g., as hypothesized for some South Atlantic occurrences based on Leg 73 drilling, W.E. Dean, personal commun.) or from prograding deltaic complexes rich in terrestrial organic matter. Cretaceous deposits and possibly Upper Jurassic black shales as drilled in the North Atlantic on Leg 76 (R.E. Sheridan, personal commun.), as well as those on the Falkland Plateau rich in organic carbon, are of great interest both from the standpoint of exploration for hydrocarbons and the perspective of changes in deep circulation and ocean chemistry.

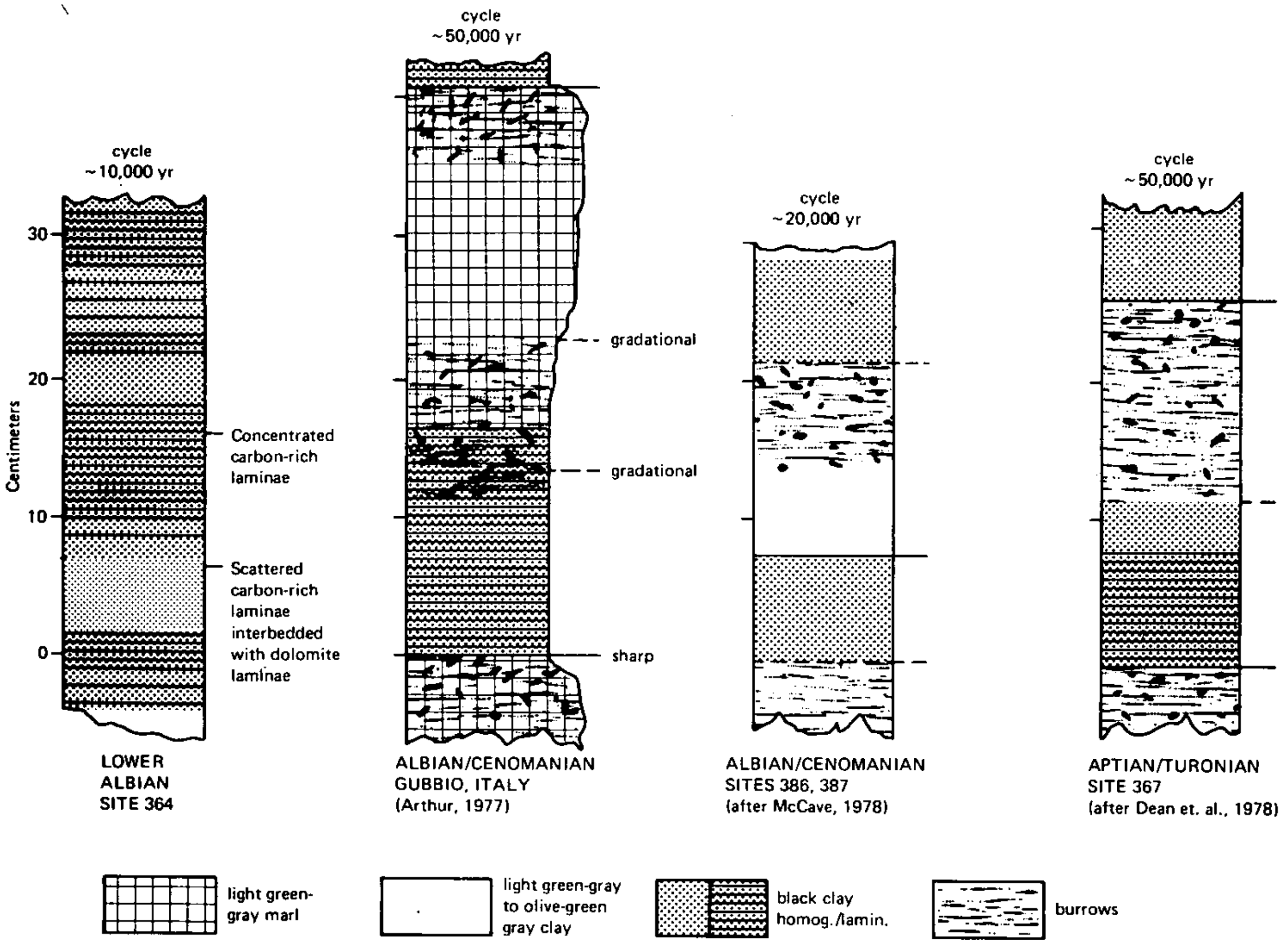


Figure 10. Cretaceous marine black shale-limestone (or marl) cycles. Note alternation of dark-colored, organic-rich, laminated mudstone with burrowed, light-colored limestone (after Arthur and Natland, 1979).

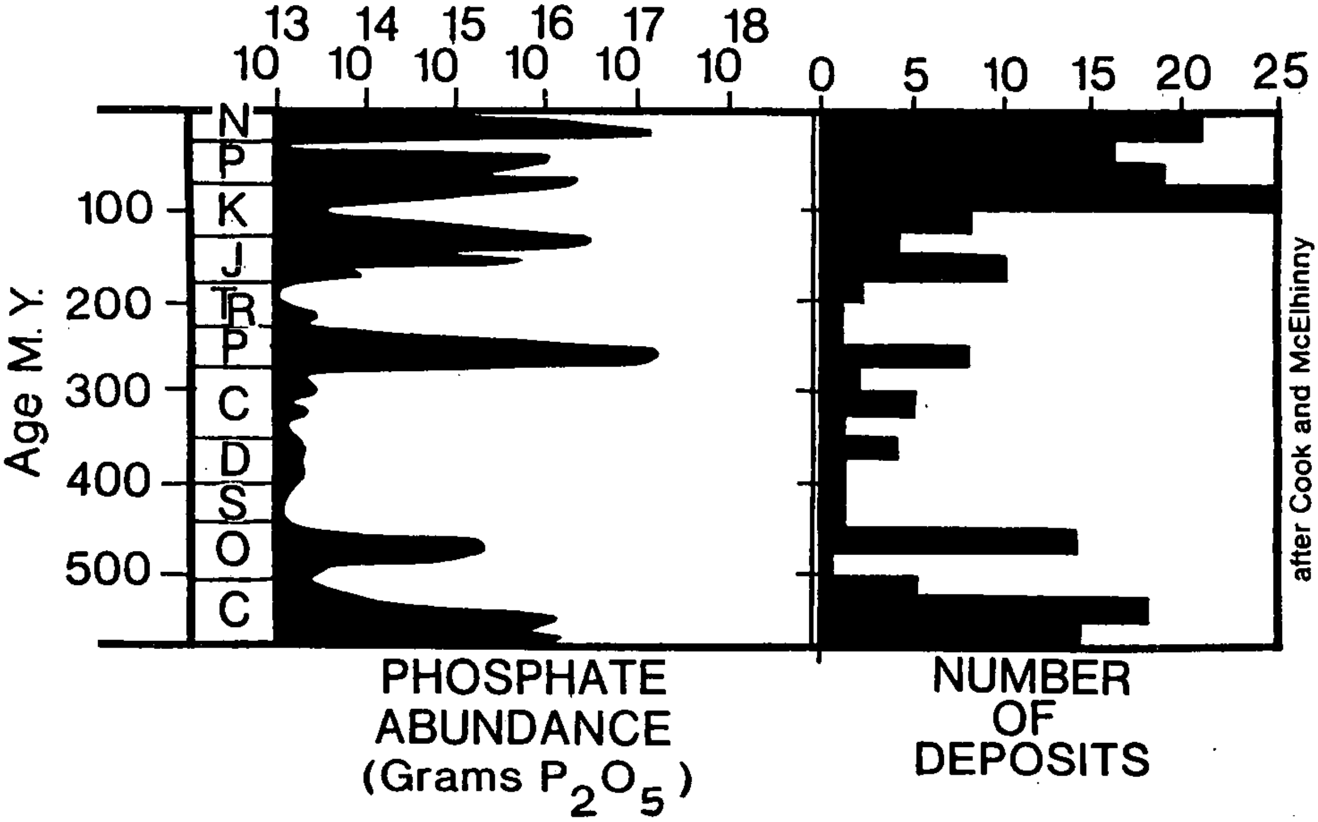


Figure 11. Episodes of major economic phosphorite accumulation (Cook and McElhinny, 1979).

Phosphatic Sediments. The origin and apparent episodicity of major sedimentary phosphorite deposits remain an important problem (e.g., Bentor, 1980; Sheldon, 1981) although a number of models have been proposed (see review in Sheldon and Burnett, 1980). Phosphatic black shales are associated with oxygen-minimum zones today (Burnett et al., 1980; Baturin, 1971), but these deposits are neither widespread nor exceptionally rich in marine apatite. Major phosphorite deposits apparently require some mechanism to concentrate them, as well as a very large supply of phosphorus. The major deposits are episodic in time (Fig. 11; Cook and McElhinny, 1979), and this episodicity probably reflects fluctuations both in supply of phosphorus to the oceans and in the processes which cause the concentration of phosphorite deposits, mainly reworking during low stands of sea level (e.g., Arthur and Jenkyns, 1981).

The supply of phosphorus to sediments for the initial formation of marine apatite is probably largely through the production and preservation of large amounts of organic matter. Thus, the phosphorite problem is, in a way, ancillary to the oxygen-minimum-zone studies (see discussion at the beginning of Section B.4). The major aspects of the phosphorite problem to be attacked are (1) episodicity in the formation of authigenic marine apatite and its association with oxygen-minimum zones, high productivity, and changes in climate and circulation; (2) the relations of sedimentary facies between organic-rich muds and, especially, diatomaceous muds and paucity of terrigenous deposition on continental slopes and outer shelves (Fig. 12); and (3) the geochemistry of marine apatites and associated pore waters and sediments.

Single or isolated opportunistic sites are not adequate to assess the above factors and trace the origin and development of phosphorite in the ocean. Transects will be required which begin in belts of phosphorite deposition in modern oxygen-minimum zones off Peru, Namibia, and southern Arabia and move downslope until the high-productivity, anoxic, phosphatic facies are lost. The holes should penetrate the complete Neogene and part of the Paleogene sequences. The chemical and mineralogical associations of phosphoritic sediments, such as the palygorskite-sepiolite problem, can also be studied in the recovered DSDP cores without superimposed effects of weathering, a common problem for studies of ancient deposits on land. This is particularly important for studies of stable isotopes and trace elements (including uranium).

Ancient marine phosphorites, which do not have continuity to the present and are particularly puzzling, include those in the middle Tertiary along the East Coast of the United States (e.g., Manheim et al., 1980) as well as those on the Chatham Rise off New Zealand (Cullen, 1980). These deposits are in part exposed by erosion, and their association with organic-rich sediment or zones by upwelling or oxygen minima remains cloudy. Hydraulic piston coring or conventional coring of transects along the western Atlantic phosphorite belt may elucidate the origin of these deposits and help relate them to phosphorites of the same age which are more obviously associated with upwelling zones.

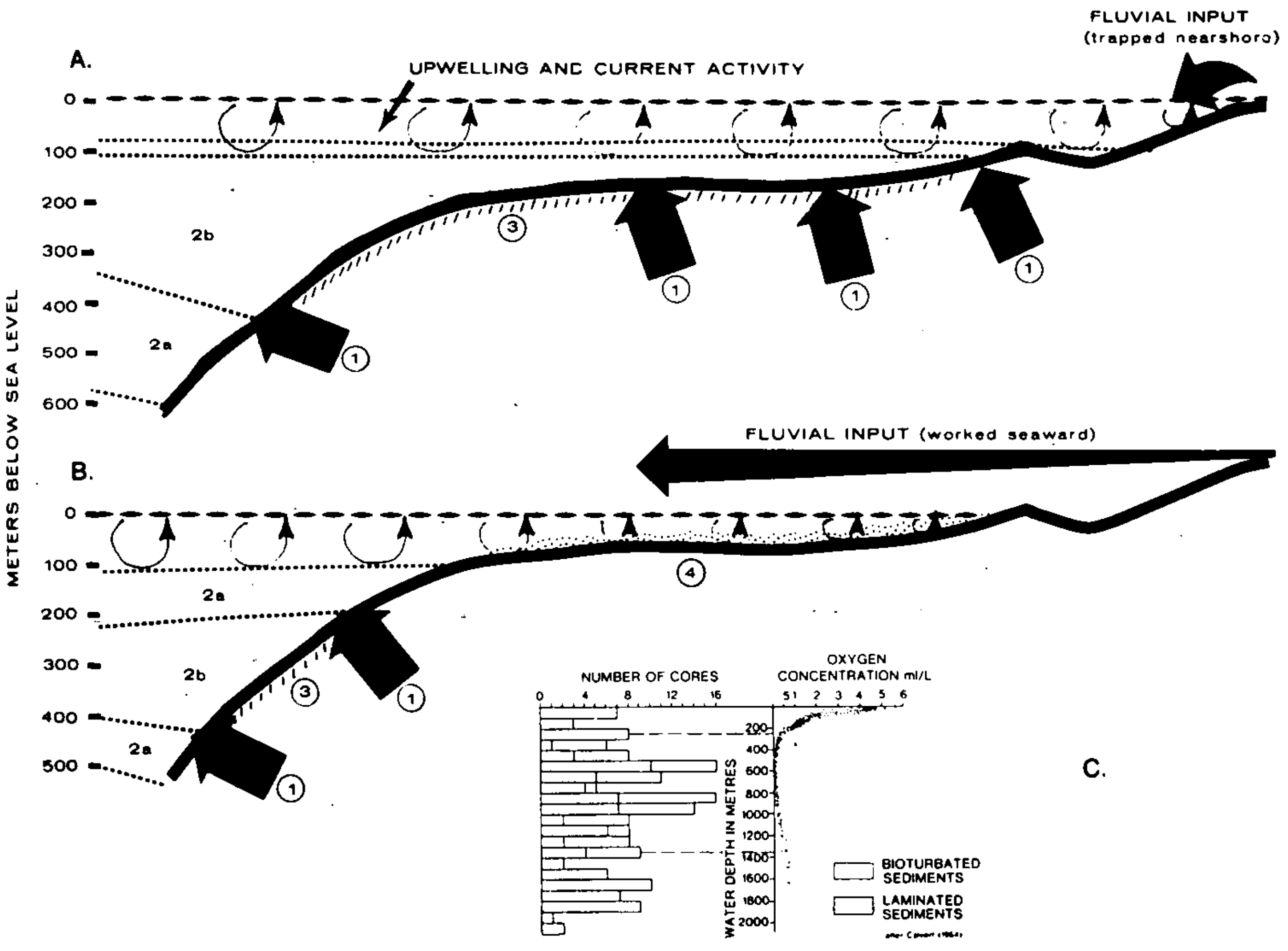


Figure 12. Changes of sea level, expansion and contraction of the oxygen-minimum zone, and changes in area of deposition of mud which is rich in organic carbon (see Arthur and Jenkyns, 1981).

B.5 Carbonate Platforms and Reefs

Quite naturally, any program of ocean drilling considers the sediments of the deep-ocean floor its main objective. We are not to forget, however, that carbonate reefs and platforms are also oceanic sediments and often have subsided to abyssal depths. They need light, warmth, and ocean water to flourish and compete with calcareous plankton for the supply of calcium to the oceans. They often grow attached to continents, but they do best where the continent provides a substrate only and none of its detritus. (See also Appendix II.)

Originally, geologic studies of modern reefs and platforms were driven almost exclusively by the need to examine modern analogues of ancient carbonate deposits. However, as research was extended to the subsurface, it turned out that modern platforms are themselves a valuable source of information on the history of the oceans (Schlanger, 1981). The following topics in particular merit attention.

Eustatic Sea Level. Theoretical work over the past decade has led to the conclusion that any eustatic movement of sea level will be distorted by loading effects and isostatic response of the lithosphere (Clark et al., 1978). In this world of relativism, the nearest approximation to a fixed gauge in the ocean is probably a small island or carbonate platform which responds as an integral part of the ocean floor. Drilling in carbonate platforms has shown that indeed the Pleistocene rises and falls of sea level are recorded as a sequence of marine sediments (high stands) punctuated by unconformities marked by karst and soils (low stands). In the Pacific, high-stand deposits have been identified at 120,000 and 235,000 years ago with major unconformities between them (Ristvet et al., 1978). Other unconformities occur throughout the Tertiary section (Schlanger, 1963), but these have not yet been correlated with the low stands of sea level predicted by Vail et al. (1977). In the Bahamas, a similar sequence of marine intervals and unconformities was obtained. Beach and Ginsburg (1980) were able to demonstrate that a major change in sediment types and spacing of the unconformities correlates approximately with the presumed onset of glaciation in the Northern Hemisphere.

Paleogeography. Reef biota generally require tropical or subtropical conditions and have thus been used successfully to define paleoclimatic belts and constrain plate motions (McKenzie et. al., 1980). In addition, the propagation of certain benthic organisms, such as corals, is strongly dependent on currents and topographic stepping stones because their life cycle includes only a short planktic larval stage. (For an example of this approach see Schlanger and Premoli-Silva (1981) on the relationship of the Caribbean and the Line Islands in the Pacific during the Cretaceous.)

Sclerochronology and the history of climate. Analogous to dendrochronology, the study of the annual banding of corals provides a detailed record of the variations of growth rate in response to changes in the environment (Knutson et al., 1972). These records can be extended several hundred years into the past and hold the promise of becoming a key to the short-term variations of climate and the effects of man-made pollution. Sclerochronology may be able to bridge the gap between the geologic record and man's detailed history of climate in the last 200 years.

Vertical Tectonics. Carbonate platforms will tend to maintain a flat top at or near sea level because abundant carbonate production is limited to the photic zone. During their period of growth, platforms therefore accurately monitor the relative changes of sea level and have been successfully used to constrain models of mid-plate subsidence (Detrick and Crough, 1978; Schlanger, 1981). Drowning or burial of platforms, on the other hand, signals significant events, such as a pulse in tectonic subsidence, a drastic change in environment, or a eustatic rise of sea level (Schlager, 1981). The geologic record shows several periods of global mass-extinction of platforms, and drilling drowned platforms is as important as drilling active reef caps. Many drowned-reef platforms have the added advantage that their tops were never exposed to fresh water and thus provide a standard for the study of diagenetic fabrics and stable isotopes.

Modern Carbonate Platforms as Facies Models. Sedimentology of recent deposits naturally emphasizes the horizontal patterns, whereas the geologic record consists essentially of vertical sequences. If modern carbonate platforms are to provide a standard for interpreting the geologic record, we have to study them in three dimensions. Drilling on the tops of flat platforms in the Bahamas has already demonstrated major changes in sediment composition and facies, which are probably related to events in Pleistocene glacial history (see Appendix II and Beach and Ginsburg, 1980). Clearly, the past is not the "Holo-Scene" projected back in time. Even less well known is the third dimension of modern platform flanks, and deep-water drilling capabilities are needed to meet this objective. Flanks can be expected to be an important element in prograding platforms commonly observed on seismic profiles. Their depositional geometry is commonly thought to reflect the rise and fall of relative sea level, but exactly how platform flanks respond to sea-level fluctuations is a matter of debate. Studies in the Bahamas indicate that sediment input from the platform is the opposite of a clastic shelf-slope system. Input is high during high stands of sea level when the platforms are flooded and decreases during low stands when the banks are exposed (Lynts et al., 1973; Crevello and Schlager, 1980). Vail et al. (1977), on the other hand, found that carbonate platforms respond to fluctuations of sea level in much the same way as clastics.

The facies pattern of platform flanks is controlled by a delicate interplay of rate of sediment input from the banks, erosion and deposition by turbidity currents and contour currents, mass-wasting processes, and submarine lithification (Mullins and Neumann, 1979; Schlager and Ginsburg, 1981). Single holes drilled by *Glomar Challenger* in some platform flanks or rises have produced significant results (Hollister, Ewing et al., 1972; Schlanger, Jackson et al., 1976; Larson, Schlanger et al., 1981), but they have not documented the geometry of flank deposits in detail. We recommend the drilling of transects of short (200-meter) holes across well-surveyed platform slopes in the Bahamas and the Pacific (e.g., Line Islands) to examine the Neogene sequence and its relation to sea level.

B.6 High Latitude Marine and Glacio-Marine Sediments

Glacially influenced marine sediments of high latitudes should be given more attention in future drilling as they can be expected to contain otherwise inaccessible information on the polar regions.

Through sporadic drilling in high latitudes, *Glomar Challenger* obtained some Cenozoic sections of high-latitude deep-sea sediments. Sedimentation turned out to be controlled by the interplay of ice-rafting, turbidity currents, and strong bottom currents. It was demonstrated that important information could be gleaned about the onset of glaciation, the extent of ice sheets, changes in sediment source, and dispersal in response to climatic changes (Piper and Briscoe, 1975; Davies and Laughton, 1972). Although speculative in many respects, these studies clearly indicate the potential of high-latitude deep-sea sediments as proxy-indicators of the waxing and waning of the polar ice caps. We recommend that a more systematic effort be made to study high-latitude marine and glacio-marine sediments, in particular through drilling on the margins of Antarctica. This effort should include transects that extend to middle latitudes in order to monitor the advance and retreat of the polar front as recorded in the migration of the circum-polar high-fertility zone (Ludwig, Krasheninnikov et al., 1980).

B.7 Rhythmic Sedimentation

Stratigraphic cycles with periods from a year (varves) up to millions of years have been demonstrated in many JOIDES boreholes, but the controls on these cycles or rhythms are poorly understood. One scale of cycle that has captured the attention of the geologic community in recent years is that related to sea-level fluctuations (ones to tens of m.y.). Another that deserves special attention is the 10^4-year cycle. Rhythmic sedimentation with periods of several tens of thousands of years is very common in both piston cores of Quaternary sediment and JOIDES cores from older stratigraphic intervals. The cycles are expressed by regular color, compositional, or diagenetic changes over intervals of centimeters to meters, depending upon prevailing sediment accumulation rates. Some better known examples from the North Atlantic are late Neogene and Quaternary carbonate cycles, Eocene biosiliceous sediments with rhythmic zones of silica diagenesis (Jansa et al., 1979), and alternating gray-green and black beds in Middle Cretaceous black shales and alternating white limestone and dark marl in Lower Cretaceous, (Dean et al., 1978; Arthur, 1979).

The causes of many of these rhythms are still unclear. Some of them have been attributed to surface-water productivity, circulation changes, or variable turbidite influx. The common forcing function in most cases may be changes in climate driven by the earth's orbital perturbations (Fischer, 1980). The rhythms deserve detailed systematic study through the entire Mesozoic/Cenozoic sedimentary record, probably on a basin-by-basin basis. In each basin the stratigraphic section must necessarily be a composite, assembled from individual boreholes where both biostratigraphy and rhythm development are best documented. Detailed analyses of the rhythms should include, where appropriate, physical sedimentology, mineral composition, stable-isotope stratigraphy, floral/faunal studies, geochemistry, diagenetic variations, and paleomagnetism.

In order to test hypotheses best on the causes of these rhythms, we need information on how they vary in space across a basin, which of them can be correlated from basin to basin, and what their exact true domain is. The drilling strategy must thus include transects across two or more ocean basins. We believe that this project can be carried out largely by using transects drilled for other purposes; e.g., Cretaceous anoxic events, studies of oxygen-minima, and carbonate dissolution profiles.

B.8 Hiatuses/Unconformities

Gaps in the stratigraphic record can be grouped loosely into three categories:

1. Gaps resulting from physical removal of sediment by bottom currents, turbidity currents, slumps, and so forth.
2. Gaps resulting from removal by dissolution of soluble carbonate or siliceous debris. This is difficult to distinguish from a situation where the geochemical environment at the sea floor simply prohibits deposition of soluble debris. In either case, some insoluble residue is deposited in an extremely condensed record that is, practically speaking, a hiatus.
3. Apparent unconformities that are defined by seismic reflection. Because the resolution of conventional seismic data is low (±20 meters), these "unconformities" may not in reality correlate with stratigraphic gaps but rather with periods of slow (pelagic) deposition.

The first category of hiatuses has been dealt with in Section B.2 under **History of Abyssal Circulation** because bottom currents are the only known mechanism for regional removal of sediment. Other mechanisms are locally important but are not dealt with here as regionally and globally significant problems.

Hiatuses resulting from occurrence of a "corrosive" sea floor environment probably can be studied best in "pelagic red-clay" sequences. A classic example is the Upper Cretaceous multicolored clay (Plantagenet Formation) of the North Atlantic (Tucholke and Mountain, 1979; Jansa et al., 1979). These are carbonate-free sediments with extremely low rates of accumulation. The continuity of their deposition is very uncertain but could be resolved by closely-spaced paleomagnetic measurements and ichthyolith stratigraphy.

The third class of "unconformity" is best studied in continental margin transects where high-accumulation environments of the upper continental rise are juxtaposed against the low-accumulation pelagic environment (Tucholke, 1981). The transect must continuously core one or more seismic sequence boundaries along a well-surveyed seismic reflection grid. The sequence boundary or boundaries should exhibit lateral changes in apparent conformity of reflectors, ranging from obvious onlap situations to correlative apparent conformities. Drilling such a transect is an obvious test of both control of sea level on sediment influx to the ocean basin and the true rock-stratigraphic nature of seismic unconformities.

B.9 Carbonate Dissolution Profiles

In situ measurements of dissolution rates in vertical profiles of the water column (Berger, 1970b; Milliman, 1975) have dramatically improved our understanding of carbonate dissolution in present-day oceans. Deep-sea drilling has established that the dissolution levels fluctuate through time. It also has been shown that variations in vertical dissolution gradients and productivity considerably change dissolution patterns (Heath et al., 1977). It is thus extremely important to study transects across topographic highs. *Glomar Challenger* has recently documented the Cenozoic fluctuations of dissolution levels in time and space by drilling a transect on Walvis Ridge (Moore, Rabinowitz et al., 1981). We are just beginning to see the results of this very promising approach and more needs to be done. The logical next steps are (1) to drill Cenozoic transects in other ocean basins, such as the Ontong-Java Plateau or the East Pacific Rise off Peru, in order to compare different oceans and to evaluate the effects of basin-basin fractionation and (2) to study in detail the "warm" periods, such as the Eocene and the mid-Cretaceous, when predominantly salinity-stratified oceans may have had far more variable dissolution profiles than we see today (Berger, 1979).

B.10 Tectonic Setting and Sediment Facies

Without tectonics, sedimentation would soon grind to a halt. Tectonics thus represents a first-order control on sedimentation, and Section C (mass balances) deals with some aspects of this relationship. This section draws attention to another facet of the general topic of tectonics and sedimentation — the influence of specific plate-tectonic settings (such as oceanic trenches, back-arc basins, or continental rises) on facies patterns and stratigraphic sequences (Dickinson, 1974).

The provenance of sand has been shown to reflect distinctly the plate-tectonic setting (Dickinson and Valloni, 1980). Past cruises of *Glomar Challenger* have observed that facies and facies succession both carry the signature of specific tectonic settings. The backarc basins of the western Pacific are one example that appears to be characterized by a recurring sequence of depositional systems (Klein, 1975; White et al., 1980). The sequence of depositional systems in other domains is perhaps less well understood. Oceanic trenches, forearc basins, oceanic rises, continental slopes, and mid-oceanic ridges, amongst other domains, are all areas of active deposition of sediment; yet no attempt has been made to determine which systems of deposition are diagnostic of these terrains, which are characteristic of one or more terrains, and whether, in fact, a predictive order of depositional systems can be recognized in each domain.

C. GLOBAL SEDIMENTARY MASS BALANCES

C.1 Sedimentation in the Deep Sea — A Balance Between Supply and Removal

The rate of accumulation of biogenic and clastic sediments in the global ocean has varied significantly over the last 100 m.y. as illustrated by the results of deep-sea drilling (Davies and Worsley, 1981; Southam and Hay, 1981; Arthur, 1981). Interpretation of the pattern of variations through time suggests that global *sea level*, *tectonics* and *climate* exert a first-order control on accumulation rates of deep-sea sediment. Variations in global sea level apparently induce sympathetic fluctuations in the rate of accumulation of deep-sea sediment through so-called shelf-basin fractionation. This means that during global transgressions, more clastic sediment and carbonate is trapped on the continental shelves and in epicontinental basins, and less is available for burial in deep-sea basins. The opposite situation is expected during regressions. Increased global or local tectonism can overprint this pattern. But to some extent tectonism and global sea level are also linked. Episodes of continental uplift and mountain-building, for example, appear to correspond to low stands of sea level. Because of these feedbacks, we expect generally high deep-sea sedimentation rates during periods of regression and high global tectonism. Certain tectonic events may also cause abrupt changes in the patterns and rates of sediment accumulation in the deep sea. An example of this effect may be the sudden isolation and evaporation of large ocean basins (see Section C.5). Global climate also produces an imprint on patterns of deep-sea sedimentation, on both supply and removal processes. Climate influences supply largely by changing the rates of continental run-off and weathering, which causes variations in the amount of clastic detritus in the dissolved components reaching the oceans. Oceanic *fertility fluctuations* through time are undoubtedly influenced by changes in rates of *chemical weathering* on land. Climatic changes also produce changes in water-mass structure, temperature, and chemistry. Increases and decreases in rates of deep-water production and circulation, temperature, and oxygen and CO^2 contents modify the patterns of sediment supply by increasing or decreasing rates of carbonate or silica dissolution and sediment winnowing, erosion, or transport (see Section B.2).

Obviously, changes in configuration of continents, tectonism, sea level, and climate are interrelated to a great extent, and, therefore, it is difficult to separate their relative effects on marine sedimentation and sediment budgets. Ideally, we would first like to establish a general background pattern of sediment accumulation in the deep sea — a sort of average. Ocean drilling will contribute significantly toward this goal through continuous updating and refinement of studies of global sediment masses and sedimentation rates. As a second step, we would concentrate on studying and identifying the causes of *major* deviations from expected trends; for these will provide us with the best information on non-steady-state excursions of the global ocean chemical-sedimentary system. Studies of global sediment budgets and patterns of accumulation through time relate to a number of individual efforts to which we attach importance, some of which have already been discussed. These are (1) Paleogene global sediment budgets, (2) sedimentology of deep marine hiatuses (Section B.8), (3) the evolution and sedimentology of contourite drifts (Section B.2), (4) carbonate dissolution transects (Section B.9), (5) marine evaporite "giants," and (6) global "fractionation" mechanisms (high-low latitude; shelf-basin; and basin-basin). Each of these programs requires a different strategy for site selection, and specific site placement or drilling transects are advisable for optimum resolution of some of them. The problems of fractionation between shelf and basin (during the Paleogene), among basins, and between areas of high and low latitude are discussed below; another chapter deals with marine evaporites.

C.2 Paleogene Sediment Budget

Paleogene deep-sea sequences probably give us the best opportunity to study global variations in deep-sea sedimentation as a function of global sea level, climate, and other factors in a largely non-glacial world. Preliminary results of deep-sea drilling suggest that major changes in global deep-sea sediment accumulation patterns and rates occurred during Late Paleocene through Oligocene time (Fig. 13). These patterns are obviously not a simple reflection of sea-level variations and shelf-basin fractionation as outlined in Section C.1. For example, during the early to middle Eocene, rates of carbonate and organic carbon accumulation in the deep sea reached a maximum, while the extent of shelf seas was also at a maximum and large amounts of shallow-water carbonate, organic matter, and phosphorite accumulated in shelf sequences. This and other evidence (e.g., Arthur and Jenkyns, 1981) suggest that the flux of dissolved constituents to the oceans was greater during the late Paleocene to middle Eocene, and that the alkalinity and fertility of the oceans was significantly

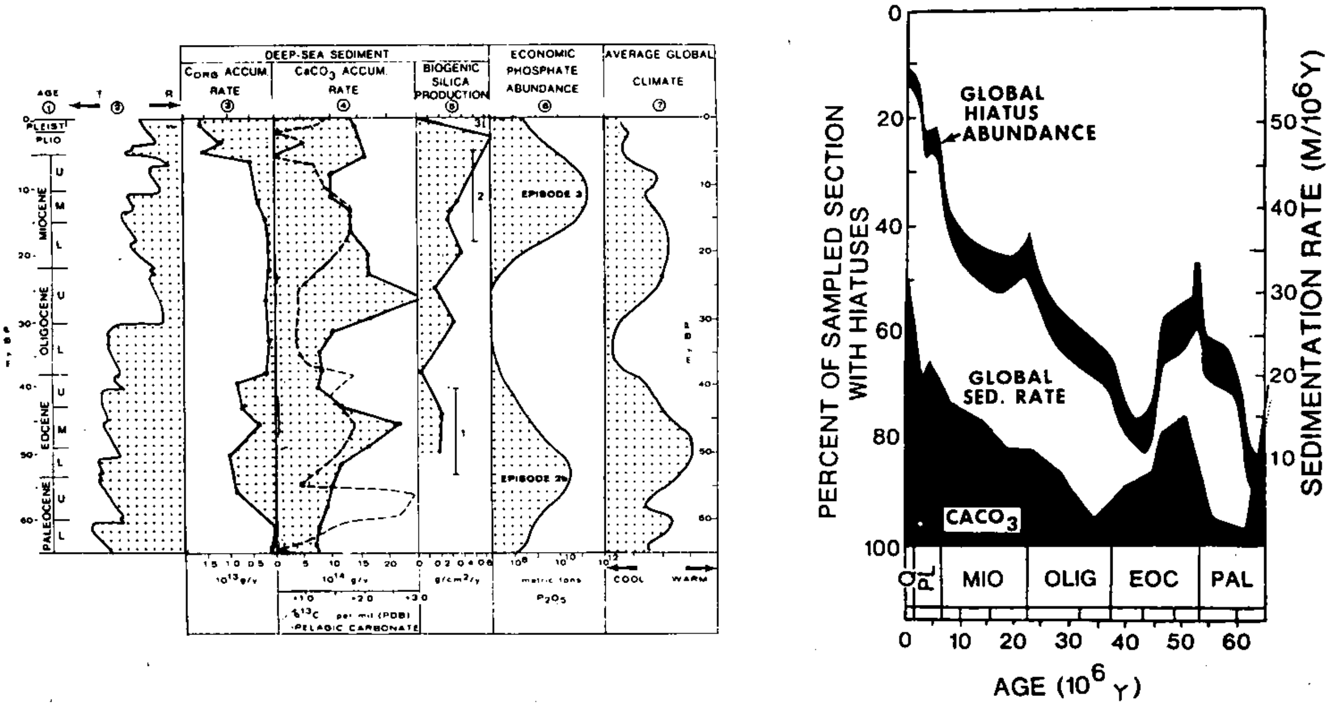


Figure 13. Left — Changes in sea level and rates of accumulation of organic carbon, carbonate, and silica in the deep sea during the Cenozoic (after Arthur and Jenkyns, 1981). Right — Global rates of accumulation and hiatus episodes in the deep sea during the Cenozoic (modified from Berger, 1979).

greater than before or after this time. Curiously, the rapidly shrinking area of shallow seas in the late Eocene to middle Oligocene coincided with an abrupt decrease of accumulation rates of both clastic and carbonate sediment in the deep sea. Thus, at least in this part of the Cenozoic, there was not a simple play-off between sea level and sediment accumulation rates on shelves and in basins. We conclude that other factors, such as climate, dominated the sedimentation system. We also know that a significant change in deep circulation occurred near the end of the Eocene, nearly coincident with climate and changes of sea level although this remains to be clearly demonstrated.

The relationships described above lead us to suggest the Paleogene as a primary target for ocean sedimentation-geochemical studies. Sites should be located in all major ocean basins to recover thicker sequences of Paleogene deep-sea sediment for high-resolution biostratigraphic, sedimentological, and geochemical studies. Paleodepth transects could be targeted to interface with problems of Sections B.2 and B.8 outlined above and should be so located as to eliminate the current geographic and paleodepth bias to DSDP sites.

C.3 Basin-Basin and Latitudinal Fractionation

Global geochemical cycling through time is complex and difficult to study. To a large degree, the relationships outlined in Section C.1., in Section C.2., and in this chapter will become clear only after a considerable amount of drilling has been completed, and some of the answers will "fall out" from drilling related to other objectives. However, we again emphasize that care must be taken to recover continuous sequences with broad geographic coverage and paleodepth range.

In calculating accumulation rates and assessing distribution patterns of sediment and chemical elements through time, the effects of shelf-basin fractionation (Section C.2) will not be the only consideration. We cannot achieve our goal of examining changes in chemical fluxes to the oceans by studying the variation of output in one particular basin. The response of ocean chemistry to changes in sea level, climate, and/or ocean circulation patterns is globally integrated, but the response may vary from one basin to another. Berger (1970a) coined the term "basin-basin fractionation" to explain why, for example, the North Atlantic basin is a carbonate sink, while the Pacific is a silica and organic carbon sink at present. This chemical fractionation is due to the site and mode of deep-water formation and the progressive increase in the age of deep water in the direction of deep circulation. At present, the North Atlantic has young, oxygenated deep waters that are not so corrosive to carbonate; the Pacific has largely old, oxygen-depleted, nutrient-enriched, corrosive deep-water masses. Therefore, the modern pelagic sedimentary record is somewhat different in each basin. This effect must be considered as a variable in studies of the ancient record. The mode of deep-water formation and the direction of deep-water flow undoubtedly varied with time and were very different for periods such as the Paleogene and Cretaceous.

The effect of the area of the sea floor over which a certain type of sediment accumulates must also be considered in studies of geochemical balances. In the case of pelagic carbonate or biosiliceous sediments, this might be called "high-latitude/low-latitude fractionation." Changes in the rate of accumulation of carbonate or of biogenic silica at a given site through time could be, in part, a function of more latitudinally widespread deposition of carbonate during warm climatic episodes (e.g., Berger and Winterer, 1974) or of the inception of the circum-Antarctic silica belt during the Oligocene in conjunction with the formation of the Antarctic circumpolar current (e.g., Brewster, 1980). This again emphasizes the importance of geographic coverage of sites, including those in high latitudes. A specific target in this respect is the poorly known Arctic Ocean, which may have acted as a silica sink during the Late Cretaceous and Paleogene.

C.4 Sediment Masses of Continental Slope and Rise

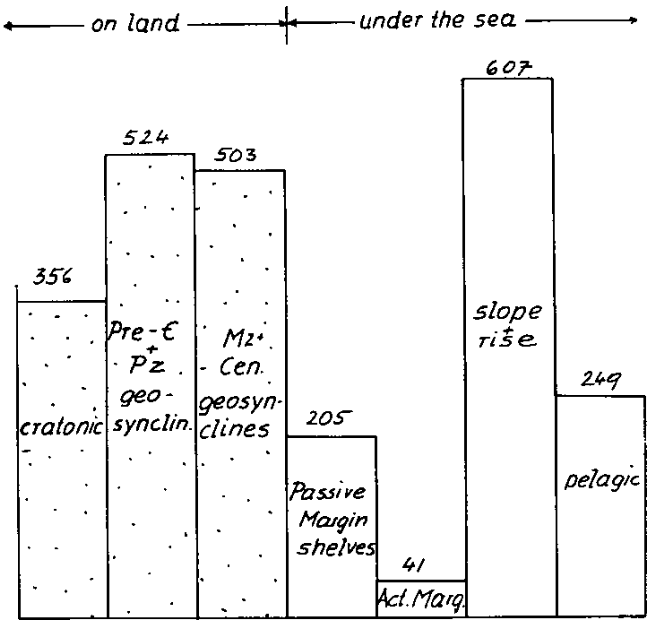


Figure 14. Sediment masses in 10^{21} grams (after Southam and Hay, 1981).

Figure 14 shows that, of the total sediment mass of the Earth, over 40% is in the ocean basins and margins (Garrels and MacKenzie, 1971; Southam and Hay, 1981). The better we know the age, volume, and composition of these sediment accumulations, the more accurate will be our estimates of the fluxes between reservoirs and the better our understanding of the interaction of the atmosphere, ocean, and lithosphere.

Sediments of continental slope and rise represent probably the biggest sediment accumulation on earth. Most of these sediments are deeply buried, and we have only a vague notion of their age and composition. Generally, pre-Tertiary rise sediments are beyond the reach of *Glomar Challenger*. Documenting composition and nature of rise sediments remains one of the prime objectives of ocean-margin drilling. However, any effort to sample rise sediments should use the hammer besides the drill. In marked contrast to pelagic sediments, rise sediments are found in large quantities and good exposures in mountain belts on land. They may provide at least some of the data needed for sediment mass balancing.

C.5 Marine Evaporite Giants

In addition to the longer term, global changes in deep-sea sedimentation caused by variations in tectonism, sea level, and climate and feedbacks between these parameters, we are just beginning to understand the potential of evaporite deposition to cause rapid changes in ocean chemistry and hence changes in climate, ocean circulation, productivity, and patterns of deep-sea sedimentation (Arthur and Kelts, 1979; Hay, 1981; Arthur, 1981). Extensive evaporite deposition has been touted in the past as the cause of brackish oceans and the extinctions at the end of the Permian (e.g. Fischer, 1964). There is now some information to suggest that evaporite basins are relatively short-lived, and that great volumes of evaporites can be deposited in a short (e.g., less than 1 or 2 m.y.) period of time. The rapid deposition of large volumes of chemical sediments has the potential of perturbing ocean chemistry (Fig. 15). For example, it is estimated that deposition of 2 x 10^6 km³ of gypsum and halite occurred in 2 m.y. or less in the restricted Angola-Brazil Basin of the South Atlantic during the Aptian. This event is hypothesized to have caused a reduction

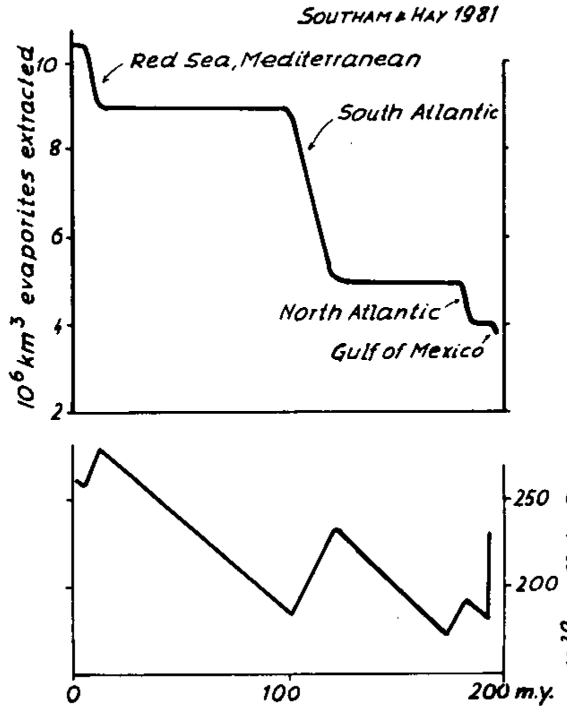


Figure 15. Extraction of evaporites from the ocean and content of chlorine in the ocean (after Southam and Hay, 1981). Deposition of evaporite giants must have a profound effect on salinity of the world ocean. Drilling is required to determine the exact age and composition of these deposits and refine the rough estimates shown above.

in mean ocean salinity of 5 to 7 ppt, and to have seriously affected the cycling of calcium, sulfur, and other elements, which may be evidence in the record of carbonate dissolution and sulfur isotopes (e.g., Arthur and Kelts, 1979). Restricted evaporite basins may also act as pulsing sources of dense saline water to the rest of the world ocean (e.g., Thierstein and Berger, 1978; Arthur and Natland, 1979), and these may induce or enhance stable density layers and deep-water oxygen deficits.

At present, we know very little about the age, rate of deposition, composition, and volume of the four major ocean-basin evaporites accessible to deep-sea drilling. These are the Upper Jurassic Louann Salt of the Gulf of Mexico, the Jurassic(?) salt of the North Atlantic (Nova Scotia, Morocco, etc.), the Lower Cretaceous evaporite of the South Atlantic and the Upper Miocene (Messinian) evaporites of the Mediterranean. Drilling of several parts of each evaporite deposit will be necessary to provide information on the sequence of evaporite deposition (e.g., number of events of basin filling), the details of the composition of the evaporites (e.g., was the ratio of Ca/Mg/Na to S/Cl in sea water different at each time than that at present), and the age, volumes, and total time represented by each deposit. (It is quite possible that new Stassfurt-type deposits of late-stage evaporites will be discovered.) In this way we will be able to better constrain models relating evaporite deposition to changes in ocean chemistry and circulation.

C.6 Diagenesis and Global Cycling of Elements

At present, we have little quantitative knowledge on how diagenesis of deep-sea sediments affects the global cycling of elements. When piston cores 10-15 meters long are studied at high resolution, the data show a variety of concentration gradients and anomalous mineral zones (Emerson et al., 1980; Klinkhammer, 1980). *Glomar Challenger's* hydraulic piston cores provide an opportunity to document these changes over much longer time spans and over a wider range of diagenetic stages.

It is proposed that a detailed, inorganic geochemical study of sections of hydraulic piston cores be undertaken. Geochemically active zones can be quickly identified using pH and sulfide probes. Subsampling, pore water removal, and detailed geochemical analyses from these zones would provide a data base to identify and evaluate the nature of the geochemical equilibrium. Model estimates for diffusive, advective, and geochemically reactive processes would allow comparisons to be made between elements and depths and thus would be useful in evaluating the geochemical activity of various sedimentary environments. Data of this kind can be expected to significantly improve our understanding of deep-sea sediments as transient reservoirs in the global cycling of chemical elements.

C.7 Carbon and Sulfur Cycles

It is now well established that the ratios of $^{13}C/^{12}C$ and $^{34}S/^{32}S$ have varied considerably throughout the Phanerozic and seem to be inversely correlated (Fig. 16). These variations indicate changes in the size of and the fluxes between reservoirs — carbonate sediments and buried organic matter for carbon, and evaporites and pyrite (in shale) for sulfur (Garrels and Lerman, 1981).

The long and almost continuous cores produced by the Deep-Sea Drilling Project have been used successfully to separate this global signal from other effects such as biogenic fractionation and post-depositional exchanges.

Significant results are to be expected in the future from continued analysis of carbon and sulfur isotopes in deep-sea cores and concomitant determination of the carbon-sulfur ratio of shales. One hypothesis that needs to be tested, for example, is the concept of Holland (1973), expanded by Veizer et al. (1980), of a simple "zero-order" relationship between the carbon and sulfur cycles: "oxygen produced by photosynthesis of carbon dioxide and burial of organic carbon is used up by oxidation of pyrite sulfur to sulfate. Conversely, oxygen produced by biological reduction of sulfate to sulfide and its fixation as pyrite is used up by oxidation of organic carbon to carbon dioxide."

D. POST-DEPOSITIONAL ALTERATION OF SEDIMENTS

Research on post-depositional alteration of sediments is intimately tied to measuring physical and chemical properties in the stratigraphic column. Work in this field has steadily gained momentum during the Deep-Sea Drilling Project and the past 5 years saw major contributions particularly through downhole measurements and sampling of in situ pore water. With these new techniques, it is now possible, for instance, to address the question of submarine hydrology (Section D.7) in a systematic way. On the other hand, it is equally essential to continue (and improve) standard measurements of such parameters as porosity, density, acoustic velocity, etc. These data significantly contribute, for instance, to calibration of seismic profiles by DSDP boreholes and to geophysical modelling of margin subsidence.

Studies on sediment diagenesis are generally less specific in terms of location than other projects. Addressing problems pointed out in this report thus commonly involves only measuring certain parameters while drilling for other purposes. Exceptions to this rule are the proposed transects in a silica-rich horizon, certain hydrothermal studies, and phosphorite transects.

D.1 Alteration of Carbonate Minerals

The study of DSDP holes (Schlanger and Douglas, 1974) and oil wells in Cretaceous chalk (Scholle, 1977) has provided us with a good understanding of the basic trends in diagenesis of carbonate ooze. A most significant question that remains is the effect of diagenesis on the stable isotope record of carbonate skeletons (Veizer and Fritz, 1976). Criteria for distinguishing unaltered from slightly altered skeletons need to be refined and continuously updated based

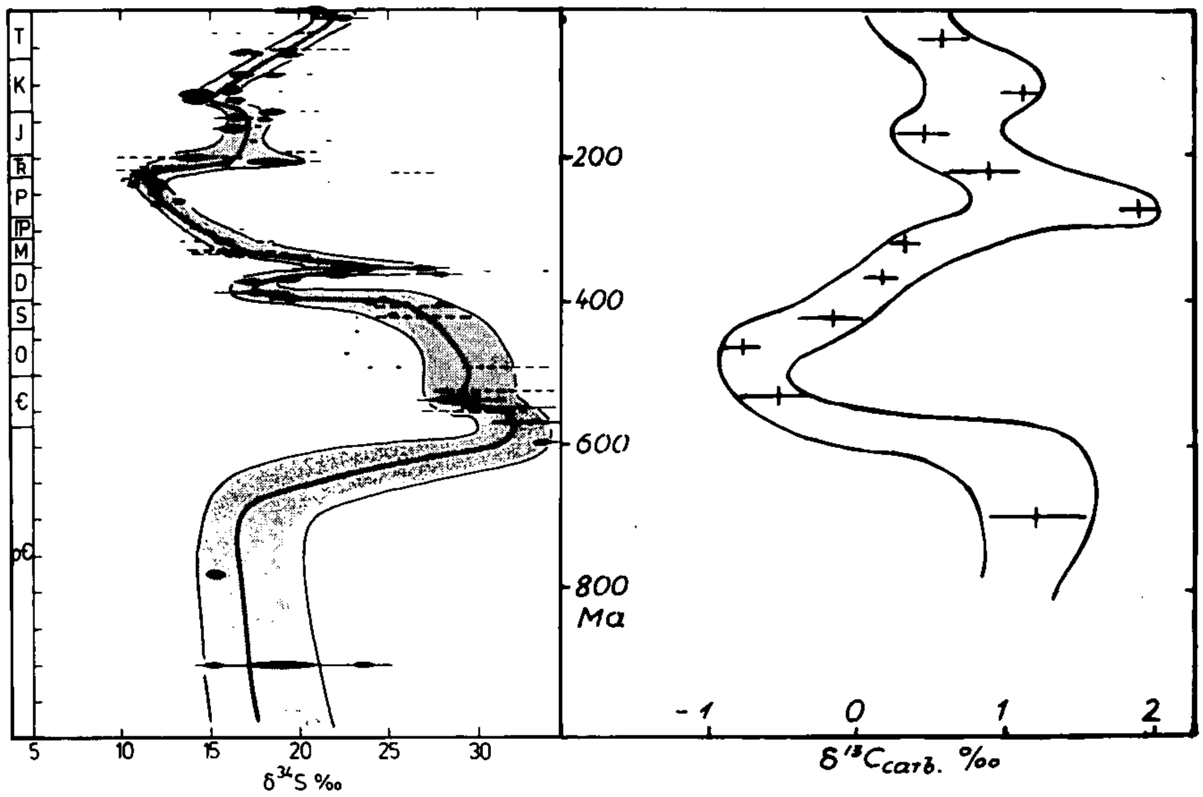


Figure 16. Variation of carbon and sulfur isotopes (in carbonate and sulfate, respectively) show a negative correlation, suggesting a direct coupling of sulfur and carbon cycles through photosynthesis and oxidation of pyrite sulfur to sulfide. Ocean drilling can provide the data necessary to accurately define this relationship. Data from Claypool et al. (1980, sulfur) and Veizer at al. (1980, carbon).

on such characteristics as ultra-structure and trace-element signature. All too often the criterion for acceptance or rejection of isotope data is whether they "fit the curve." Special attention should be paid to carbonate sediments that were originally rich in metastable components such as aragonite and magnesium calcite which dissolve rapidly and form overgrowths on calcite grains.

Another open question concerns the composition of very light oxygen isotopes that pelagic chalks acquire under deep burial. Is this signature the result of equilibration with hydrothermal waters, or is it simply the result of dissolution/precipitation in a nearly closed system of pores under steadily increasing temperatures?

Work on carbonate diagenesis will probably not require special drilling. Most of it can be carried out as an ancillary project, in part even by using already existing core material.

D.2 Silica Diagenesis

Despite fairly extensive study of cherts and siliceous sediments recovered by the Deep-Sea Drilling Project (e.g. Riech and von Rad, 1979; Pisciotto, 1981), it still has not been demonstrated unambiguously which geologic factor or combination of factors (temperature, depth of burial, time, sediment composition) has controlled the rate and nature of silica diagenesis. This is partly a result of the fact that a drilling program has not been designed specifically to address the silica diagenesis problem and partly a result of poor core recovery from cherty horizons. Experimental studies of silica diagenesis have provided good information on the possible controls outlined above (e.g., Kastner et al., 1977), but these results remain to be directly applied and confirmed in the deep-sea record.

We suggest that this question be studied in a carefully selected grid of drill sites that is designed specifically to look at one "time-stratigraphic" chert horizon such as Eocene Horizon "A" in the North Atlantic. Several holes penetrating this horizon where it is in both a carbonate and clay-rich facies and has had similar temperature and depth-of-burial histories will help resolve the question of control by sediment composition. Similarly, a group of holes recovering the cherts from a variety of depth/temperature regimes (i.e., on crust of different ages) in sediments of largely the same composition will help resolve the question of control by depth of burial and temperature. These tests should be accompanied by a suite of pore-water geochemical measurements. Furthermore, the drilling technology necessary to assure the most complete recovery of cherts and interbedded, less lithified sediments should be maximized. Ancillary to this will be the recovery of more complete sequences of siliceous biogenic sediment for studies of biostratigraphy and rate of accumulation. The origin of such widespread silica-rich deposits at certain times in the past, such as during the Eocene, remains a perplexing problem.

D.3 Diagenesis of Clays and Related Phases

Changes in composition of solid mineral particles are sensitively signalled by changes in the composition of pore fluids. The great body of information from routine analysis of pore fluid in all DSDP/IPOD legs is summarized in Gieskes (1981). These data point to uptake of magnesium and potassium in clays and other silicates, selective loss of sodium and calcium, and transformation of authigenic silica to complex phases. In areas of red clay, devitrification of volcanic ash results in formation of philipsite, clinoptilolite, and other zeolites.

The palygorskite-sepiolite group of clay minerals is surprisingly common in DSDP core material. Based on computer analysis of the data file tapes, palygorskite has been observed more frequently and in greater quantity than both chlorite and kaolinite in ocean cores according to Hathaway (1979). Yet origin of palygorskite remains unsettled, some authors (e.g., Chamley, 1981) preferring a land-derived detrital origin, and others concluding that authigenic formation from biogenic silica may be dominant. This problem could be attacked effectively by a sequence of holes in major phosphorite belts, such as those off Peru-Chile and North Africa, on the Chatham Rise, off southwestern Africa, or in the northwestern Indian Ocean off Somalia. It will be important to document carefully lithochemical changes in the transition from organic- and phosphate-rich sections to pelagic sediments.

Another problem involves the transformation of montmorillonite-smectite to illite-mixed layer minerals under the influence of increasing temperatures. This releases water and is believed to affect petroleum migration. Very useful data could be obtained by observing sequences of smectite-rich clays exposed to high temperatures in the vicinity of igneous bodies, particularly on the East Pacific Rise. Such studies might fit in very well with hydrothermal and hydrologic studies referred to in sections D.2 and D.6.

Much attention has been drawn to problems of sediments derived from alteration of basaltic rocks at the boundary of Layers 1 and 2 (Gieskes and Lawrence, 1981). Nontronite and nontronitic smectite been found widely. Theoretical studies of basalt alteration by sea water have shed much light on the chemical exchanges and transformations to be expected at various temperatures and water-rock ratios. However, there is still controversy about whether palagonite and ash can be converted to clays without hydrothermal influence. Kurnosov et al. (1980) state categorically that hydrothermal exposure is required. Careful monitoring of temperature conditions and modelling of presumed paleotemperature in conjunction with hydrogeologic transects could calibrate authigenic clay-temperature systems. We may then be able to use particular clay species as paleoenvironmental indicators.

D.4 Alteration of Organic Matter

Postdepositional alteration of sediments could be studied based on alteration of the organic constituents. These are very sensitive to changes in physical or chemical environments. Broadly, three very sensitive stages are distinguished:

1. Early diagenesis in young sediments, where bacterial activity is the main source of transformation.
2. Diagenesis, where low-temperature chemical transformations and organic-inorganic interactions are predominant.
3. Catagenesis, where thermal reactions generate petroleum and wet gas.

Diagenesis is particularly well covered by DSDP/IPOD type of drilling as it extends over a depth range from about 10 to 1000 or 1500 meters. This interval has been seldom investigated for scientific purposes, as oceanographers usually core the interval between 0 and 10 meters, and petroleum industry takes cores mainly over the sections which can yield petroleum accumulations, i.e., beyond 1000 meters.

Over that shallow interval, organic matter is particularly sensitive to temperature history, and many chemical rearrangements of the biological markers have been documented and provide an insight to thermal history. This aspect could be especially valuable in rift and other sediments subjected in the past to high geothermal fluxes where it could be a tool for reconstruction of the past geothermal situation. Present and ancient spreading zones, such as the Gulf of California and the East Pacific or Indian Ocean rises could be adequate locations for that purpose. For further topics, see Appendix I.

D.5 Gas Hydrates

Gas hydrates are ice-like, crystalline lattices formed by physical bonding of gas and water. They form under high-pressure, low-temperature conditions where enough gas is present to exceed the saturation limits in water. The pressure/temperature conditions are met over a substantial portion of the sea floor, and gas concentrations appear to be high enough that hydrates occur in many sea-floor locations. Most of these occurrences have been predicted by observation of a bottom-simulating reflector (BSR) several hundred meters below the sea floor. This reflector often cuts across bedding planes, and it is thought to mark the base of the hydrate zone (the level of phase boundary below which hydrate is no longer stable because of increasing temperature with depth below sea floor). Hydrates have been recovered by deep-sea drilling both in areas with a BSR (Blake Outer Ridge, using pressure core barrel, PCB) and without a BSR (slope of the Middle America Trench).

A variety of outstanding questions remain about the formation and occurrence of gas hydrates:

1. Do they form a low-permeability lattice that prevents significant gas migration? (Do they cap large gas deposits?)
2. Does the phase boundary at the base of the hydrate zone have other geochemical effects (e.g., mineralization)? Significant quantities of siderite cored near the level of the bottom-simulating reflector at DSDP Sites 102, 103, and 104 (Hollister, Ewing et al., 1972) indicate the possibility of mineralization under the influence

of gas.

3. Is the formation of hydrates affected by the texture and composition of the sediment?
4. How is the conductivity (and geothermal gradient) affected by the formation of hydrates?
5. What is the source of gas in the hydrates (biogenic production within the hydrate zone or migration from deeper, thermogenic sources)?
6. Why do hydrates sometimes occur without the presence of a bottom-simulating reflector?
7. Do hydrates facilitate slope failure in the tectonically deformed and steepened accretionary wedge of active margins?

These questions merely "scratch the surface" of a series of interesting geochemical, sedimentological, and geophysical problems. Gas hydrates should be cored with the PCB in both coarse-grained and fine-grained sediments, then isolated in a pressure and temperature controlled chamber for study of physical characteristics (e.g., conductivity, velocity) and chemical characteristics. Heat-flow and conductivity measurements in the borehole are critical, as is borehole logging (e.g., sonic velocity).

D.6 Hydrothermal Sediments

One of the scientific milestones of the past 5 years of oceanic research has been the discovery of active submarine hydrothermal discharge areas which are associated with deposition of metalliferous precipitates. The metal-rich sediments include both oxidized, manganese-rich deposits, first observed in the Galapagos Rift Zone "mounds" and subsequently drilled during Leg 70, and reducing, polymetallic sulfide deposits, first discovered by the French scientists with the *Cyana* submersible (Hekinian et al., 1980). The new data (A. Malahoff, personal commun.; R. Koski, personal commun.; both at the 12th Underwater Mining Institute), accompanied by SEABEAM mapping, show deposits hundreds of meters long and many meters in thickness, with indications that the floors and margins of virtually every major fast-spreading rift system may have extensive hydrothermal activity. Slower spreading rifts in areas such as the FAMOUS and TAG hydrothermal fields (Rona, 1978) have only thin, surficial hydrothermal metalliferous deposits.

Heretofore, virtually all information on hydrothermal sedimentary deposits has been surficial, with the exception of the Leg 70 drillings in the Galapagos mounds province where some 30 meters of sediment was encountered. Future targets for investigation of the effect of convective migration through deeper sediments would probably involve several criteria: a fracture zone or other tectonic area permitting deep penetration of fluids into young crust, evidence of surficial metalliferous deposits, a large negative heat flow anomaly indicating actual convection of heat by fluids, and a flankward wedge of sediments reaching several hundreds of meters in thickness. R. P. von Herzen and F. L. Sayles and the JOIDES Hydrogeology Working Group (R. Anderson, personal commun.) seem to have identified some potential target areas for studying hydrothermal sediments. One such is an area on the western flank of the East Pacific Rise around 4°-5°N and 110°-120°W.

One should emphasize that good transects may shed light on phenomena occurring over a very large area, virtually the entire seismically active area of the eastern Pacific from 55°N to 60°S. The DSDP leg tentatively scheduled for 1983 to investigate hydrothermal phenomena on the East Pacific Rise is a first step in this direction. We expect, however, that the problems of hydrothermal sediments (and thermally driven circulation in sediments) will resist quick solutions and will require drilling for years to come. Transects specifically including thick wedges of sediment will be needed.

D.7 Hydrology

Background. Hydrology is defined here as the study of the nature and movement of fluids in ocean sediments and rocks — their role in transporting heat and dissolved substances, altering pre-existing rocks, and forming new sediments and mineral products.

Early pore-fluid studies in DSDP drilling concluded that in most analyzed holes, molecular diffusion rather than physical advection dominated movement of dissolved species in sediments (Sayles and Manheim, 1975). Evidences of hot fluid discharge in the Red Sea Rift Valley (Degens and Ross, 1969) and indirect evidence of hydrothermal activity in the East Pacific Rise (Bostrom and Peterson, 1966) were considered exceptional phenomena.

During the 1970's geophysicists concluded that water must circulate in areas of newly formed igneous crust (Lister, 1981), but it was not until the dramatic discoveries in the Galapagos area that thermally driven convection systems in permeable igneous formations became apparent.

A variety of new tools to implement hydrologic studies have been developed or applied in the course of the scientific drilling program. These include the *pressure core barrel* to recover cores and gas under in situ pressure and the Barnes *in situ fluid sampler* to permit acquisition of more reliable samples of fluids and their ephemeral properties. In 1979 the first hydrologic experiment was conducted on Leg 69 (Galapagos area) when pack-off experiments attempted to recover pore fluid from basaltic rocks. To date virtually no reliable information on pressure gradients has been available from deeper sedimentary formations. Such data are critical to assess pathways of movement and velocities. A revitalized downhole measurement panel focused attention on the importance of geophysical logging, which can provide data on hydrologic parameters. A meeting on measurements-while-drilling convened in Washington under sponsorship of JOI-NRC to explore the status of rapidly emerging downhold telemetry techniques to obtain real-time or near real-time measurement of formation and engineering parameters. These techniques offer special possibilities for measuring pressure and temperature and other important parameters related to hydrology, as well as for increasing the safety and efficiency of operation in riserless boreholes.

Important hydrologic problems. A key question is the degree to which hydrothermal convection can move fluids through sediment wedges on the flanks of active spreading centers or other areas where deep hydrologic circulation may be induced. Previously mentioned sites (approximately 4°-6°N, 160°W) in the East Pacific Rise area may be ideal for such activity. The working group on hydrology has proposed investigation of the hydrology of the "black smoker" regions of the eastern Pacific. Ideally *2-km penetration* is desired to investigate fluid and chemical fluxes in sediments and sedimentary rocks as well as igneous rock. Similar tests in slower-spreading regions, such as the Atlantic and Indian Ocean rifts, would also be desirable if sufficiently well-consolidated formations can be found. Another promising target is the Gulf of California where the spreading centers are buried by sediment because of high rates of deposition and the narrow shape of the basin.

Compactional loss of fluid and pathways for such loss are still poorly understood in spite of the widespread occurrence of this phenomenon in thick, continental margin sediment wedges. This problem can be attacked by acquisition of comprehensive sedimentological and chemical (interstitial water) data in a series of holes across rapidly thinning strata over a relatively impermeable base (Fig. 17). Accurate porosity and sedimentary petrographic data, complemented by chemical data on fluid and gas composition including isotopes in water and dissolved gasses where possible, should provide tracers for the movement of fluids. Good geophysical logging should likewise provide background to assess hydraulic permeability.

Attention is being redirected to the concepts of Johnson (1940) and Manheim (1967) regarding submarine discharge of fluids from truncated continental margin strata during the Wisconsin glacial maximum. In principal, a 100-meter hydraulic head (owing to drop of sea level) could power discharge as deep as 4000 meters below sea level. Such discharge may have helped carve submarine canyons and other features on the continental margin by sapping. It could be investigated by studies of pore fluid in 500- to 1000-meter deep holes at the region of the shelf break along Atlantic and Pacific continental margins of the United States, as well as other areas having flat-lying, continental shelf strata.

In active margins the expulsion of pore fluids can be expected to proceed much faster than in passive margins because subduction actively carries sediments down into high-pressure regimes.

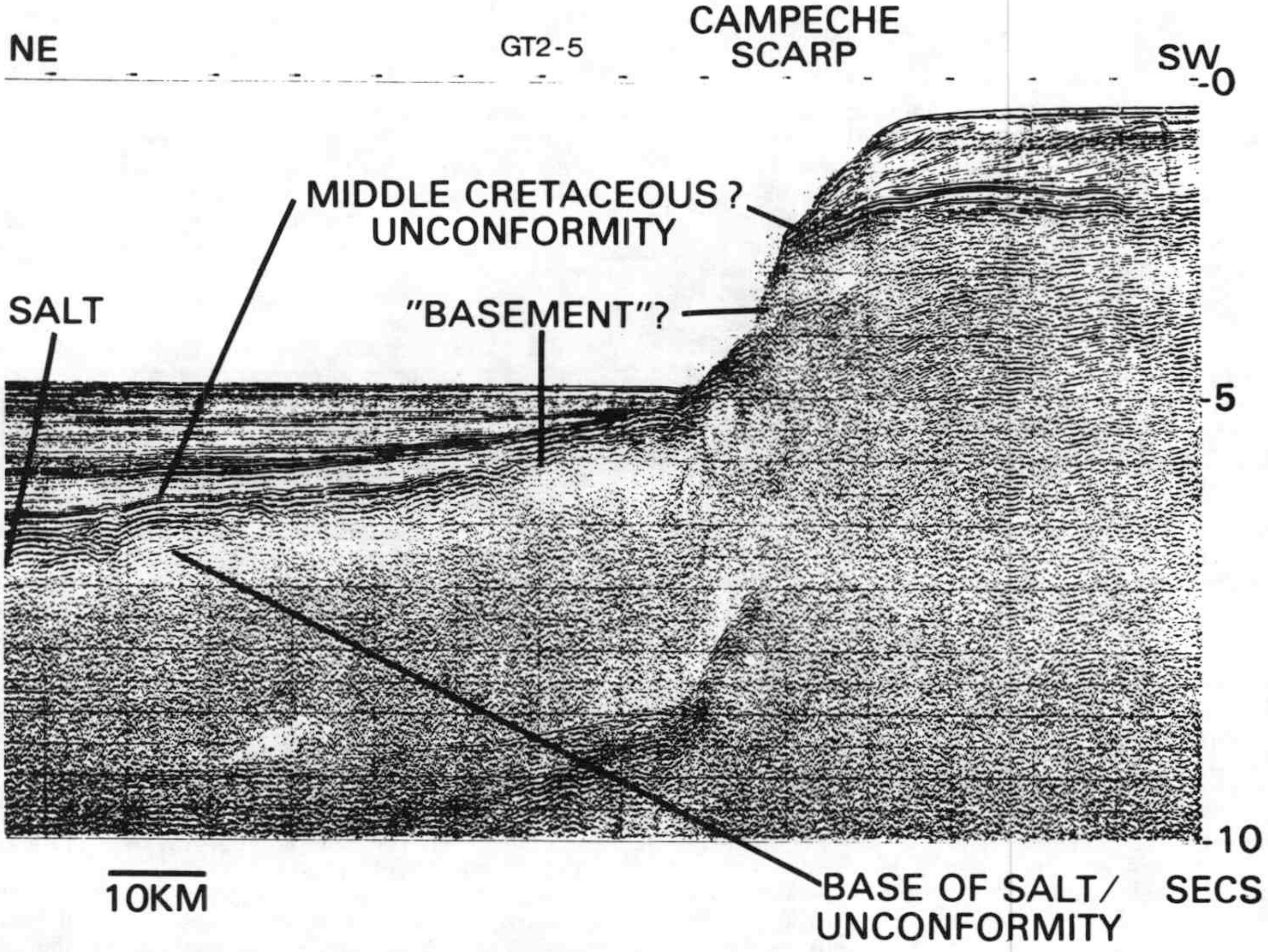


Figure 17. Rapidly thinning strata overlying impermeable salt and basement provide ideal sites to study compaction under variable overburden. Salt brines will serve as tracers for migration of pore fluid. Example from southern Gulf of Mexico, after Buffler et al. (1980).

E. SUMMARY

It is now widely accepted that the fluctuations of *sea level* relative to the continents exert a strong control on shelf sedimentation. There is no consensus, however, about whether deep-sea sedimentation directly responds to these changes, how deep circulation varies in response to sea level, and whether the low-stand unconformities on the shelves extend into the deep sea. Transects across seismically well-documented passive margins are needed to answer these questions.

Abyssal circulation has been shown to profoundly influence sedimentation; but we have no clear picture of the history of bottom circulation, nor is there an unambiguous set of criteria to recognize deposits of contour currents. It is recommended to drill systematically large contourite drifts and to document the history of Cenozoic bottom circulation and its water sources in both the northern and southern polar regions.

Gravity displaced sediments present two fundamental problems that need to be tackled by drilling:

1. Modern *submarine fans* require three-dimensional control to develop a unifying concept of fan deposition. Until now, studies on modern fans focused on morphology and surface sediments; studies on ancient fans focused on the vertical sequence. Only drilling in modern fans can close this gap.
2. Large *slumps* (and associated debris flows) seem to have formed in many places on today's continental slopes and moved out onto the upper rise. Verification of this process through drilling would profoundly influence concepts on slope stability.

Sedimentation in oxygen-deficient oceans during the Cretaceous, the middle Jurassic and the Eocene is both scientifically puzzling and economically significant (petroleum source rocks). Oxygen-deficiency seems to be linked to periods of equable climate and low oceanic temperature gradients for which the present-day oceans present a poor analogue. We recommend a concerted effort on "anoxic events," including studies of small-scale analogues in modern oceans and basin-transects in the Cretaceous and Eocene.

Formation of *marine phosphorites* which requires a delicate interplay of high organic production, low oxygen levels, and fluctuations of sea level should be studied in drilling transects across Neogene oxygen-minimum zones in modern upwelling areas.

Carbonate platforms are oceanic sediment piles that contain a wealth of information on paleoclimate and the surface water masses as well as on sea level and vertical tectonics. Modern platforms also provide widely used models for ancient carbonate deposits. Most targets can be reached by relatively inexpensive drilling in shallow water and on land.

Glacially influenced sediments at high latitudes can serve as proxy-indicators of the waxing and waning of ice sheets, but systematic drilling is needed. The margins of Antarctica are particularly important targets.

Rhythmic sedimentation with periods of 10^4 yr is common in the geologic record (e.g. Quaternary carbonate cycles, Eocene siliceous "cycles," and Cretaceous oxic/anoxic rhythms). Systematic studies of continuous cores should focus on the origin of these rhythms, for instance the question of control by the Earth's orbital perturbations.

Hiatuses and unconformities are widely used as sequence boundaries in seismic stratigraphy, yet their origin is poorly understood. The formation of hiatuses by dissolution events and the formation of quasi-hiatuses by extremely slow, but continuous, pelagic sedimentation need particularly to be tested by the drill.

Carbonate dissolution profiles on topographic highs, already a target of present drilling, deserve continuous attention and should ultimately include dissolution profiles during periods of oxygen deficiency in the oceans.

The *tectonic setting* very often leaves a characteristic signature in the sediment facies and their change through time. Synthesis of ocean drilling data can be expected to define better depositional patterns in specific tectonic domains, such as passive margins, beach-arc basins, trenches, etc. No specific drilling is requested for this objective.

Mass Balance. Accumulation of biogenic and terrigenous material in the oceans has varied considerably throughout the Cretaceous and Cenozoic. Tectonics, sea level, and climate seem to exert a first order control. Attempts to separate the effects of these processes will have to rely heavily on information from the record of the abyssal circulation, marine evaporite giants, and carbonate dissolution. In addition, we recommend a concerted effort to improve world-wide coverage of the Paleogene interval, in particular in the high latitudes to reconstruct the sediment budget before and after Oligocene drop of sea level and to assess the effect of basin-basin and latitudinal fractionation of sediments. Another important drilling target are the sediments of continental rises, which represent one of the largest and least known sediment accumulations on earth.

Much work on *post-depositional alteration of sediments* can be carried out as ancillary projects using material drilled for other purposes and making optimum use of in situ measuring techniques such as pressure core barrel and pore-water sampler. The following problems require a specific drilling strategy.

To examine the effect on *silica diagenesis* of temperature, time, and pressure versus sediment composition, it is recommended to drill Eocene Horizon "A" in the Atlantic in (1) areas of constant overburden but varying composition and (2) areas of varying composition but constant overburden.

The key problems in *hydrology* require several drilling projects. The extent to which hydrothermal convection can move fluids through sediments should be studied in deep holes (2 km) on the flank of a fast-spreading ridge, such as the East Pacific Rise. Work on fluid migration through compaction requires transects in thick, continental margin sequences, ideally in rapidly accumulating strata overlying an impermeable base.

F. APPENDIX I. ORGANIC GEOCHEMISTRY — MAJOR TOPICS FOR OCEAN DRILLING

JOIDES Paper on Organic Geochemistry, B.R.T. Simoneit, Chairman

The applications of organic geochemistry can provide considerable insight into problems of broad interest to the earth sciences in all oceans.

Sedimentary organic matter can be divided into three operational categories: (1) interstitial gas, in particular methane, (2) the part which can be extracted with organic solvents (lipids, bitumen) and (3) the major solvent-insoluble residue (kerogen). Gases are usually analyzed by gas chromatography. The lipids extracted from a sediment are usually fractionated by chromatographic methods and then analyzed by gas chromatography-mass spectrometry to afford identification and quantification of individual compounds, including stereochemical definition. The insoluble organic matter (kerogen) is normally subjected to microscopic study and, more recently, to pyrolysis, oxidation, and other procedures which yield lipids that can be characterized by the methods above. Additionally, information on stable isotopes, especially ^{13}C, and other methods are often employed on whole or partial fractions of organic matter.

Oxygen Minima and Upwelling. The Miocene, particularly the late Miocene, is a period when organic-rich sediments became widespread. Their geochemistry must be examined in more detail in order to reconstruct what happened in paleoenvironments of continental margins during Miocene times. Obviously, upwelling intensified and oxygen-minimum zones grew, allowing more organic matter to be preserved. Diatomites are widespread, as is phosphorite, attesting to a massive global supply of nutrients (perhaps by circulation of nutrient-rich and previously stagnant masses of ocean water). These locations are places where sedimentation is often rapid and, therefore, the hydraulic piston corer can penetrate deeper due to delayed consolidation of sediment (eg., 292 meters at Site 532).

Drilling beneath upwelling centers and beneath major eastern boundary currents should be carried out to examine when organic enrichment (i.e., upwelling) began. This has been done in a limited way off California (Site 467), off southwestern Africa (Sites 532 and 362) and also off northwestern Africa. But more drilling needs to be carried out in a systematic study on a global basis. There may have been profound changes in the nutrient balance of the ocean in Miocene times, and this is a topic worthy of investigation. More sites need to be chosen to examine the oxygen-minimum zone along margins where upwelling is active (eg., in the Indian Ocean, the Somali Current area off western Arabia and Somalia, as well as the upwelling areas off both western India and the American continents, eg., California and Peru). This program can be greatly improved by application of the hydraulic piston coring system.

Black Shale Events. A more extensive examination of the mid-Aptian/Cenomanian section should be conducted to test in detail the concept that there were three oceanic anoxic events which all influenced the deposition in these units. At the same time, this would yield detailed data of the microstratigraphy and would allow an examination of the changes from organic-rich to organic-poor layers that are supposed to recur every 20,000-50,000 yr. in the mid-Cretaceous.

Clarification of the differences between the Albian/Aptian shales containing moderate organic carbon and the Cenomanian units with higher organic carbon is needed. This refers to the western North Atlantic Ocean where some of this work has been done at Sites 386 and 387. Furthermore, a drilling transect across the western margin (slope and rise) of the North Atlantic could examine variations of sedimentological and geochemical facies within the interval of the mid-Cretaceous black shale. The key question here is how rapidly and by how much does the section and its organic matter become more terrestrial (i.e., more gas-prone) near shore. Sites landward and seaward of Site 105 would help to solve this problem.

Other areas of interest to supplement existing data and to elucidate voids are the mid-Cretaceous off Spain and between Site 120 and Vigo Seamount.

The concept of mid-Cretaceous anoxic events needs further examination in the Pacific Ocean around the flanks of features like the Lord Howe Rise, the Shatsky Rise, or the Campbell Plateau in the southwestern Pacific. Sites should be chosen also to determine the probable location of the Cretaceous oxygen-minimum zone, as deep waters are likely to have been oxidizing during that time.

Organic-rich black shales from the mid-Cretaceous section have also been recovered from the Indian Ocean at Sites 258 and 263. These findings need to be followed up in detail to see if there are extensive black shales in the Indian Ocean.

There are very few organic geochemical analyses of these deposits. The question regarding their extent and the reasons for their formation remains open. Drilling may provide answers to these paleoenvironmental problems.

The Jurassic is another target horizon that merits more work, especially in the North Atlantic. The recent discovery on Leg 76 of Callovian black shales makes the problem of the paleoenvironment especially interesting. Deposits like these are widespread in Europe and elsewhere, but in the Kimmeridgian rather than the Callovian. Two apparently different depositional regimes can be compared and contrasted, namely, European and western North Atlantic deposits. Organic geochemistry will play an important role in unravelling the paleoenvironmental history of the Jurassic.

The Terrestrial Component - Fans and Eolian Sediments. Potamic and eolian transport of terrestrial detritus, including organic matter, followed by turbidity redistribution, are the major mechanisms for supplying continental material to hemipelagic sediments. The study of deltaic fans will result in some evaluations of the nature and magnitude of the organic detritus reaching the ocean by potamic transport. Hydraulic piston coring will be very desirable. Eolian transport is a lower-level mechanism reaching over greater geographic areas (eg., fallout from trade winds over the North Atlantic). It is of interest to define further this transport mechanism in the Neogene and also to assess if very long-range transport (eg., from southwestern North America to mid-Pacific) can contribute any significant terrestrial organic matter to the oceanic sediments.

Thermal History and Active Hydrothermal Systems A better and more reliable reconstruction of paleotemperatures in deep-sea sediments is certainly a fundamental problem of future research in DSDP/IPOD.

So far, most deep-sea sediment samples have been found to be relatively immature or only marginally mature with respect to hydrocarbon generation. A relatively young age of sediments, shallow depths of burial, and a low-temperature gradient are responsible for immaturity. Improved knowledge about diagenesis and catagenesis of different types of organic matter (kerogen) has shown that the onset of hydrocarbon generation cannot be defined satisfactorily by assuming a 0.5% vitrinite reflectance value as the threshold for hydrocarbon generation. Furthermore, in the past, hydrocarbon generation in most instances has been tested and defined by investigations considering the $C^{15}+$-hydrocarbon fraction. The very significant C^{2}-C^{15} fraction, with few exceptions, has been largely neglected. Yet it is the hydrocarbons of low molecular weight which are not synthesized by organisms, and hence they are a very sensitive indicator for thermally controlled generation of hydrocarbons.

Light hydrocarbons are more water-soluble than their higher homologs. Furthermore, among the various species, such as aromatics of low molecular weight saturated cyclic and branched-chain compounds, there are greater differences in their individual mobility in the water-saturated, subsurface environment. Therefore, light hydrocarbons are better suited to study hydrocarbon transport in sediments. Aside from problems concerning hydrocarbon redistribution or migration, this matter of hydrocarbon transport of compounds of low molecular weight is of utmost importance as a proximity indication for hydrocarbon accumulations in connection with safety measures in deep-sea drilling. It is, therefore, important to continue and even enlarge research on light hydrocarbons in DSDP.

Since immaturity is due to low geothermal gradients, as in the Japan Trench, such areas provide good tests for slow diagenetic reactions. The aim is, therefore, to define a series of molecular markers with different specific transformations over temperature and matrix ranges analogous to the clay mineral transformations.

Actively spreading oceanic basins (eg., Guaymas Basin) or ridges (eg., East Pacific Rise) should be examined further in terms of thermal effects on sedimentary or possibly "igneous" organic matter and of the resultant hydrothermal circulation moving organic pyrolysate. Various data from Leg 64 in Guaymas Basin indicate that the sedimentary organic matter is pyrolyzed near the intrusive sills, and the expended organic matter (amorphous carbonaceous residue) remains behind while the pyrolysate, consisting of gas ($C^{1-10}+$, solution and diffusion) and bitumen (C^{10}-$C^{40}+$, in water "solution"), moves with the hydrothermal fluids to the seabed, both throughout the sediment body and via conduits to vents. At the vents the bitumen forms petroleum condensates. An active hydrothermal area with an extensive sediment blanket also should be compared with a bare igneous vent area to determine the nature of the organic matter emanating from the latter. The detailed characterization of these condensates from active, sediment-covered, hydrothermal systems may yield a temperature scale and gradient for such areas, complementing the temperature data from the hydrothermal inorganic phases.

Production of Organic Matter in Divergent Zones. The record of organic matter preserved in ocean sediments can provide information about the productivity of surface waters and the types of organisms contributing to this productivity, thus complementing the paleontological record. Because fluctuations in oceanic surface currents over geological time have caused changes in productivity, study of the sedimentary organic geochemical imprint contributes to reconstruction of paleocirculation of the oceans and the atmosphere. In the interesting situation where oceanic plates move under zones of high productivity, such as the Pacific equatorial divergence, the organic content of deeper sediments may be quite different from that expected from present-day conditions. The equatorial Pacific and the Arctic (Bering Sea) and Antarctic areas are important components that will provide further information on global productivity and its history.

G. APPENDIX II. SOME OF THE PRINCIPAL RESULTS OF RESEARCH ON THE THIRD DIMENSION OF QUATERNARY CARBONATES, 1969-1981

Prepared by R.N. Ginsburg, I.G. MacIntyre, and E.A. Shinn

Annual Banding in Coral Skeletons (Sclerochronology). That the skeletons of reef-building corals have annual bands like tree rings has been known since the 1930's (see Ma, 1937), and during the 1960's an attempt was made to use banding in fossil corals to estimate changes in the length of the year (Wells, 1963). In the last decade the use of x-radiography and geochemical analyses to decipher banding in core borings of corals has led to a new generation of research that includes comparative study of growth rates (Buddenmeier et al., 1974) and the record of extraordinary events: unusually cold winters (Hudson et al., 1976), onset of man-made pollution (Dodge et al., 1974), and the beginning of the industrial revolution and nuclear testing (Druffel and Linick, 1978).

Buddenmeier, R.W., Maragos, J.E., and Knutson, D.W., 1974, Radiographic studies of reef coral exoskeletons: Rates and patterns of coral growth: Exper. Marine Biology and Ecology Jour., v. 14, p. 179-199.

Dodge, R.E., and Thompson, J., 1974, The natural radiochemical and growth records in contemporary hermatipic corals from the Atlantic and Caribbean: Earth and Planet. Sci. Letters, v. 23, p. 313-322.

Druffel, E.M., and Linick, T.W., 1978, Radiocarbon in annual coral rings of Florida: Geophys. Res. Letters, v. 5, p. 913-916.

Hudson, J.H., Shinn, E.A., Halley, R.B., and Lidz, B., 1976, Sclerochronology: A tool for interpreting past environments: Geology, v. 4, p. 361-364.

Ma, T.Y.H., 1937, (Title not available): Paleontolog. Sin. XVI B, p. 426.

Wells, J.W., 1963, Coral growth and geochronometry: Nature, 197, p. 948.

Syndepositional Diagenesis in Holocene Reefs. Prior to the 1960's it was generally believed that cementation in the marine environment was restricted to the intertidal zone (beachrock). Then beginning about the mid 1960's there were reports of submarine cementation from a number of different areas: Caribbean hardgrounds, Bahama Banks, oceanic seamounts, and the Persian Gulf. These discoveries stimulated explorations into reefs, and the result was a series of reports describing extensive cementation in reefs from Bermuda, Jamaica, and Belize. This complex of new findings has led to the recognition that most of the void-filling, fibrous cements of many fossil reefs are also syndepositional.

Foundations, Anatomies, and Growth Rates of Holocene Reefs. Drilling and seismic profiling have, in general, confirmed the long-held views that the relief of foundations largely controls the locations and gross morphology of many Holocene reefs and reef complexes. The most common foundation is Pleistocene limestone, usually reefal. There are also examples of Holocene reefs growing on elevations composed of siliciclastic sediments.

Relief triggers the initiations of reefs, but in some circumstances changes in relief brought on by rising sea level can lead to the demise of reefs. Flooding of the flat-topped Bahama Banks, for example, led to the smothering of early Holocene fringing reefs by off-bank transport of lime sands from the shallow bank. If the locus of Holocene reef growth was determined by the occurrence of Pleistocene reefs, one is naturally led to consider the origin of Pleistocene reefs. A first step in that direction has been made in Belize where seismic profiles show that some Pleistocene lagoon reefs are positioned on the elevations (banks of channels and bars) of a preceding coastal plain of siliciclastic sediments. Elevations seem to trigger reef growth, but once established, reefs can mask initial relief.

Accumulation rates vary considerably, depending on the dominant corals forming the reef framework and on the rate of rise of sea level taking place at the time of reef growth. Rising seas and fast growing corals such as *Acropora palmata* or *Acropora cervicornis* can yield up to 15 m/1000 yr. Considerably lower rates of accumulation are associated with reef facies developing under conditions of stable or slowly rising sea level — rates that range from about .5 to 4 m/1000 yr in Bermuda, the Caribbean, and Hawaii.

Closely spaced core holes or exposures in Holocene reefs have provided a broad insight into modern-reef community succession. Not only do these studies provide ideal analogues for comparative investigations of fossil reefs, but they can also help us to explain the present-day status of Holocene reefs. In some locations the reefs have been shown to have developed naturally to a stage of postclimactic degradation — St. Croix, Panama, and Florida.

Evolution of Deposition during the Plio-Pleistocene. Core borings into Pacific atolls and into the carbonate platforms of southern Florida and the Bahamas have established that shallow-water carbonates record on two levels the glacially induced fluctuations of sea level: 1) a distinctive record of low stands in the zones of discontinuity that are characterized by features of subaerial exposure (caliche-like crusts, solution features, root structures, etc.) and 2) major changes in deposition that occur at the beginning of increased glaciation (mid-Pleistocene).

Multiple, laterally continuous zones of subaerial discontinuity have been mapped by borings on Eniwetok, in southern Florida, and in Great Bahama Bank. Both the Floridian and Bahamian platforms show significant changes in depositional facies from Pliocene to Holocene. Southern Florida, for example, was transformed from an area of deposition of quartz sand to one in which carbonates predominate. Core borings on Great Bahama Bank reveal a change from an atoll-like pattern in the lower Pliocene to a flat-topped bank of non-skeletal lime sands and islands in the Pleistocene.

H. REFERENCES

Almagor, G., and Garfunkel, Z., 1979, Submarine slumping in continental margin of Israel and northern Sinai: Am. Assoc. Petroleum Geologists Bull., v. 63, p. 324-340.

Arthur, M.A., 1979, North Atlantic Cretaceous black shales: The record at Site 398 and a brief comparison with other occurrences, *in* Ryan, W.B.F., Sibuet, J.C., et al., Initial reports of the Deep Sea Drilling Project, Vol. 47, part II: Washington, D.C., U.S. Govt. Printing Office, p. 719-751.

Arthur, M.A., 1981, The carbon cycle: Controls on atmospheric CO^2 and climate in the geologic past, *in* Berger, W.H., and Crowell, J.C., eds., Pre-Pleistocene climates: Washington, D.C., Natl. Research Council — Geophys. Study Group Pub. (in press).

Arthur, M.A., and Jenkyns, H.C., 1981, Phosphorites and paleoceanography, *in* Berger, W.H., ed., Ocean geochemical cycles: Oceanologica Acta, Spec. Issue, Proceedings of the 26th International Geological Congress, p. 83-96.

Arthur, M.A., and Kelts, K.R., 1979, Evaporites, black shales and perturbations of ocean chemistry and fertility: Geol. Soc. America Abs. with Programs (Ann. Mtg.), v. 11, n. 7, p. 381.

Arthur, M.A., and Natland, J.H., 1979, Carbonaceous sediments in the North and South Atlantic: The role of salinity in stable stratification of Early Cretaceous basins, *in* Talwani, M., Hay, W., and Ryan, W.B.F., eds., Deep drilling results in the Atlantic Ocean: Continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 375-401.

Arthur, M.A., and Schlanger, S.O., 1979, Cretaceous "oceanic anoxic events" as causal factors in development of reef-reservoired giant oil fields: Am. Assoc. Petroleum Geologists Bull., v. 63, p. 870-885.

Barker, P.F., Carlson, R.L., Johnson, D.A., et al., 1981, Deep Sea Drilling Project Leg 72: Southwest Atlantic paleocirculation and Rio Grande Rise tectonics: Geol. Soc. America Bull., v. 92, p. 294-309.

Baturin, G.N., 1971, Stages of phosphorite formation on the ocean floor: Nature, v. 232, p. 61-62.

Beach, D.K., and Ginsburg, R.N., 1980, Facies succession, Plio-Pleistocene carbonate, northwestern Great Bahama Bank: Am. Assoc. Petroleum Geologists Bull., v. 64, p. 1634-1642.

Bentor, Y.K., 1980, Phosphorites — the unsolved problems, *in* Bentor, Y.K., ed., Marine phosphorites; geochemistry; occurrence; genesis: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 29, p. 3-18.

Berger, W.H., 1970a, Biogenous deep-sea sediments; Fractionation by deep-sea circulation: Geol. Soc. America Bull., v. 81, p. 1385-1402.

Berger, W.H., 1970b, Planktonic foraminifera: Selective solution and the lysocline: Marine Geology, v. 8, p. 111-138.

Berger, W.H., 1979, Impact of deep-sea drilling on paleoceanography, *in* Talwani, M., Hay, W., and Ryan, W.B.F., Deep drilling results in the Atlantic Ocean: Continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 297-314.

Berger, W.H., and Winterer, E.L., 1974, Plate stratigraphy and the fluctuating carbonate line, *in* Hsu, K.J., and Jenkyns, H., eds., Pelagic sediments: On land and under the sea, Spec. Pub. Internatl. Assoc. Sedimentologists, Vol. 1: Oxford, England, Blackwell, p. 11-48.

Bostrom, K., and Peterson, M.N.A., 1966, Precipitates from hydrothermal exhalations on the East Pacific Rise: Econ. Geology, v. 61, p. 1258-1265.

Brass, G.W., Hay, W.W., Holser, W.T., Peterson, W.H., Saltzman, E., Sloan, J.L., II, and Southam, J.R., 1981, Ocean circulation, plate tectonics and climate, *in* Berger, W.H., and Crowell, J.C., eds., Pre-Pleistocene climates: Washington, D.C., Natl. Research Council — Geophys. Study Group Pub. (in press).

Brewster, N.A., 1980, Cenozoic biogenic silica sedimentation in the Antarctic Ocean: Geol. Soc. America Bull., Pt. 1, v. 91, p. 337-347.

Buffler, R.T., Watkins, J.S., Schaub, F.J., and Worzel, J.L., 1980, Structure and early geologic history of the deep central Gulf of Mexico Basin: *in* Pilger, R.H., Jr., ed., The origin of the Gulf of Mexico and the early opening of the central North Atlantic; proceedings of a symposium: Baton Rouge, Louisiana, Louisiana State Univ., p. 3-16.

Burnett, W.C., Veeh, H.H., and Soutar, A., 1980, U-series, oceanographic and sedimentary evidence in support of recent formation of phosphate nodules off Peru, *in* Bentor, Y.K., ed., Marine phosphorites; geochemistry; occurrence; genesis: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 29, p. 61-71.

Carlson, P.R., and Molnia, B.F., 1977, Submarine faults and slides on the continental shelf, northern Gulf of Alaska: Marine Geotechnology, v. 2, p. 275-290.

Chamley, H., 1981, Long-term trends in clay deposition in the ocean, *in* Berger, W.H., ed., Ocean geochemical cycles: Oceanologica Acta, Spec. Issue, Proceedings of the 26th International Geological Congress, p. 105-110.

Clark, J.A., Farrell, W.E., and Peltier, W.R., 1978, Global changes in postglacial sea level: A numerical calculation: Quaternary Research, v. 9, p. 265-287.

Claypool, G.E., Holser, W.T., Kaplan, I.R., Sakai, H., and Zak, I., 1980, The age curves of sulfur and oxygen isotopes in marine sulfate and their mutual interpretation: Chemical Geology, v. 28, p. 199-260.

Cook, P.J., and McElhinny, M.W., 1979, A re-evaluation of the spatial and temporal distribution of sedimentary phosphate deposits in the light of plate tectonics: Econ. Geology, v. 74, p. 315-330.

Crevello, P.D., and Schlager, W., 1980, Carbonate debris sheets and turbidites, Exuma Sound, Bahamas: Jour. Sed. Petrology, v. 50, p. 1121-1148.

Cullen, D.J., 1980, Distribution, composition and age of submarine phosphorites on Chatham Rise, east of New Zealand, *in* Bentor, Y.K., ed., Marine phosphorites; geochemistry; occurrence; genesis: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 29, p. 139-148.

Davies, T.A., and Laughton, A.S., 1972, Sedimentary processes in the North Atlantic, *in* Laughton, A.S., Berggren, W.A., et al., Initial reports of the Deep Sea Drilling Project, Vol. 12: Washington, D.C., U.S. Govt. Printing Office, p. 905-934.

Davies, T., and Worsley, T., 1981, Paleoenvironmental implications of oceanic carbonate sedimentation rates, *in* Warme, J.E., Douglas, R.G., and Winterer, E.L., eds., The Deep Sea Drilling Project: A decade of progress: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 32, p. 169-179.

Dean, W.E., Gardner, J.J., Jansa, L.F., Cepek, P., and Seibold, E., 1978, Cyclic sedimentation along the continental margin of Northwest Africa: *in* Lancelot, Y., Seibold, E., et al., Initial reports of the Deep Sea Drilling Project, Vol. 41: Washington, D.C., U.S. Govt. Printing Office, p. 965-989.

Degens, E.T., and Ross, D.A., eds., 1969, Hot brines and recent heavy metal deposits in the Red Sea: New York, Springer-Verlag, 600 p.

de Graciansky, P.C., Auffret, G.A., Dupeuble, P., Montadert, L., and Muller, C., 1979, Interpretation of depositional environments of the Aptian/Albian black shales on the north margin of the Bay of Biscay: *in* Montadert, L., Roberts, D.G., et al., Initial reports of the Deep Sea Drilling Project, Vol. 48: Washington, D.C., U.S. Govt. Printing Office, p. 877-908.

Demaison, G.J., and Moore, G.T., 1980, Anoxic environments and oil source bed genesis: Am. Assoc. Petroleum Geologists Bull., v. 64, p. 1179-1209.

Detrick, R.S., and Crough, S.T., 1978, Island subsidence, hot spots and lithospheric thinning: Jour. Geophys. Research, v. 83, 1236-1244.

Dickinson, W.R., 1974, Plate tectonics and sedimentation, *in* Dickinson, W.R., ed., Tectonics and sedimentation: Soc. Econ. Paleontologists and Mineralogists, Spec. Pub. 22, p. 1-27.

Dickinson, W.R. and Valloni, R., 1980, Plate settings and provenance of sands in modern ocean basins: Geology, v. 8, p. 82-86.

Dott, R.H., 1963, Dynamics of sub-aqueous gravity depositional processes: Am. Assoc. Petroleum Geologists Bull., v. 47, p. 104-128.

Emerson, S., Jahnke, R., Bender, M., Froelich, P., Klinkhammer, G., Bowser, C., and Setlock, G., 1980, Early diagenesis in sediment from the eastern equatorial Pacific: I. Pore water nutrient and carbonate results: Earth and Planet. Sci. Letters, v. 49, p. 57-80.

Field, M.E., and Edwards, B.D., 1980, Slopes of the southern California Borderland: A regime of mass transport, *in* Field, M.E., Colburn, I.P., and Bouma, A.H., eds., Quaternary depositional environments of the Pacific coast: Soc. Econ. Paleontologists and Mineralogists Pacific Station, p. 169-184.

Fischer, A.G., 1964, Brackish oceans as the cause of the Permo-Triassic marine faunal crisis, *in* Nairn, A.E.M., ed., Problems in paleoclimatology: London, Interscience, p. 566-574.

Fischer, A.G., 1980, Gilbert - bedding rhythms and geochronology, *in* Yochelson, E.L., ed., The scientific ideas of G.K. Gilbert: Geol. Soc. Amer. Spec. Pub. 183, p. 93-104.

Fischer, A.G., and Arthur, M.A., 1977, Secular variations in the pelagic realm, *in* Cook, H., and Enos, P., eds., Deep water carbonate environments: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 25, p. 19-50.

Freeman-Lynde, R.P., Cita, M.B., Jadoul, F., Miller, E.L., and Ryan, W.B.F., 1981, Marine geology of the Bahama Escarpment: Marine Geology, v. 44, p. 119-156.

Garrels, R.M., and Lerman, A., 1981, Phanerozoic cycles of sedimentary carbon and sulfur: Proc. Natl. Acad. Sci. USA, Geology, v. 78, no. 8, p. 4652-4656.

Garrels, R.M., and Mackenzie, F.T., 1971, Gregor's denudation of the continents: Nature, v. 231, p. 382-383.

Gieskes, J.M., 1981, Deep sea drilling interstitial waters: Implications for the alteration of the oceanic crusts, Layers 1 and 2, *in* Warme, J.E., Douglas, R.G., and Winterer, E.L., eds. The Deep Sea Drilling Project: A decade of progress: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 32, p. 149-167.

Gieskes, J.M., and Lawrence, J.R., 1981, Alteration of volcanic matter in deep sea sediments: Evidence from the chemical composition of interstitial waters from deep sea drilling cores: Geochim. et Cosmochim. Acta (in press).

Gradstein, F.M., Sheridan, R.E., et al., 1981 Leg 76, western North Atlantic Ocean: JOIDES Journal, v. 7, p. 29-35.

Habib, D., 1979, Sedimentary origin of North Atlantic Cretaceous palynofacies, *in* Talwani, M., Hay, W.W., and Ryan, W.B.F., eds., Second Maurice Ewing Symposium, Results of Deep Drilling in the Atlantic: Washington, D.C., American Geophysical Union, p. 420-437.

Hancock, J.M., and Kauffman, E.G., 1979, The great transgressions of the Late Cretaceous: Jour. Geol. Soc. London, v. 136, p. 175-186.

Hathaway, J.C., 1979, Clay minerals: *in* Marine Minerals: Mineralogy Soc. America, Short Course Notes, p. 132-149.

Hay, W.W., 1981, Sedimentological and geochemical trends resulting from the breakup of Pangaea, *in* Berger, W.H., ed., Ocean geochemical cycles: Oceanologica Acta, Spec. Issue, Proceedings of the 26th International Geological Congress, p. 135-147.

Heath, G.R., Moore, T.C., and Van Andel, T.H., 1977, Carbonate accumulation and dissolution in the equatorial Pacific during the past 45 million years, *in* Andersen, N.R., and Malahoff, A., eds., The fate of fossil fuel CO^2 in the oceans: N.Y., Plenum Press, p. 627-639.

Heezen, B.C., and Hollister, C.D., 1971, The face of the deep: New York, Oxford Univ. Press, 659 p.

Hekinian, R., Febrier, M., Bischoff, J.L., Picot, P., and Shanks, W.C., 1980, Sulfide deposits from the East Pacific Rise near 21°N: Science, v. 207, p. 433.

Hollister, C.D., Ewing, J.I., et al., 1972, Initial reports of the Deep Sea Drilling Project, Vol. 11: Washington, D.C., U.S. Govt. Printing Office, 1007 p.

Jansa, L.F., Enos, P., Tucholke, B.E., Gradstein, F.M., and Sheridan, R.E., 1979, Mesozoic-Cenozoic sedimentary formations of the North American Basin; western North Atlantic, *in* Talwani, M., Hay, W., and Ryan, W.B.F., eds., Deep drilling results in the Atlantic Ocean: Continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 1-57.

Jenkyns, H.C., 1980, Cretaceous anoxic events: From continents to oceans: Jour. Geol. Soc. London, v. 137, p. 171-188.

Johnson, D.W., 1940, (No title available): Geomorphology, v. 2, p. 134.

Kastner, M., Keene, J.B., and Gieskes, J.M., 1977, Diagenesis of siliceous oozes — I. Chemical controls on the rate of opal-A to opal-CT transformation — an experimental study: Geochim. et Cosmochim. Acta, v. 41, p. 1041-1059.

Klein, G., 1975, Sedimentary tectonics in southwest Pacific marginal basins based on Leg 30 Deep Sea Drilling Project cores from the South Fiji, Hebrides, and Coral Sea basins: Geol. Soc. America Bull., v. 86, p. 1012-1018.

Klinkhammer, G.P., 1980, Early diagenesis in sediments from the eastern equatorial Pacific: II. Pore water metal results: Earth and Planet. Sci. Letters, v. 49, p. 81-101.

Knutson, D.W., Buddemeier, R.W., and Smith, S.V., 1972, Coral chronometers — Seasonal growth bands in reef corals: Science, v. 177, p. 270-272.

Kurnosov, V.B., Kotov, N.V., Murdmaa, I.O., Skornyakova, N.S., Kolodevich, I.V., and Kokorina, L.P., 1980, Vulcanism and authigenic mineral formation in the ocean (Russ.), *in* Timofeev, P.P., Gramberg, I.S., and Varenstoc, I.M., eds., Morskaya and geologiya, sedimentologyiya, osadochnaya petrografiya i geologiya okeana: 26th International Geological Congress, Paris, Reports Soviet Geologists, p. 24-29.

Larson, R.L., Schlanger, S.O., et al., 1981, Initial reports of the Deep Sea Drilling Project, Vol. 61: Washington, D.C., U.S. Govt. Printing Office, 885 p.

Lister, C.R.B., 1981, "Active" and "passive" hydrothermal systems in the oceanic crust: Predicted physical conditions, *in* Fanning, K.A., and Manheim, F.T., eds., Dynamic environment of the sea floor: Lexington, MA, Lexington Books, D.C. Heath Co., p. 122-131.

Ludwig, W.J., Krasheninnikov, V., et al., 1980, Tertiary and Cretaceous paleoenvironments in the southwest Atlantic Ocean: Preliminary results of Deep Sea Drilling Project, Leg 71: Geol. Soc. America Bull., v. 91, p. 655-664.

Lynts, G.W., Judd, J.B., and Stehman, C.F., 1973, Late Pleistocene history of Tongue of the Ocean, Bahamas: Geol. Soc. America Bull., v. 84, p. 2665-2684.

Manabe, S., and Wetherald, R.T., 1980, On the distribution of climate change resulting from an increase in CO^2 content of the atmosphere: Jour. Atmos. Sci., v. 37, p. 99-118.

Manheim, F.T., 1967, Evidence for submarine discharge of water on the Atlantic continental slope of the southern United States: New York Acad. Sci. Trans., Ser. 2, v. 29, p. 839-853.

Manheim, F.T., Pratt, R.M., and McFarlin, P.F., 1980, Composition and origin of phosphorite deposits of the Blake Plateau, *in* Bentor, Y.K., ed., Marine phosphorites; geochemistry; occurrence; genesis: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 29, p. 117-137.

McGregor, B.A., and Bennett, R.H., 1979, Mass movement of sediment on the continental slope and rise seaward of the Baltimore Canyon Trough: Marine Geology, v. 33, p. 163-174.

McKenzie, J., Bernoulli, D., and Schlanger, S.O., 1980, Shallow-water carbonate sediments from the Emperor Seamounts: Their diagenesis and paleographic significance, *in* Jackson, E.D., Koisumi, I., et al., Initial reports of the Deep Sea Drilling Project, Vol. 55: Washington, D.C., U.S. Govt. Printing Office, p. 415-455.

McLean, H., 1981, Reservoir properties of submarine-fan facies: Great Valley sequences, California: Jour. Sed. Petrology, v. 51, p. 865-872.

Melosh, H.J., 1981, The mechanics of large meteoroid impact on the Earth's oceans: Abstracts, Proceedings of the Conference on Large-Body Impact, Snowbird, Utah, p. 37.

Milliman, J.D., 1975, Dissolution of aragonite, Mg-calcite and calcite in the North Atlantic Ocean: Geology, v. 3, p. 461-462.

Moore, T.C., Rabinowitz, P.D., et al., 1981, Leg 74 — Walvis Ridge: JOIDES Journal, v. 7, p. 4-17.

Moore, T.C., Van Andel, T.H., Sancetta, C., and Pisias, N. 1978, Cenozoic hiatuses in pelagic sediments: Micropaleontology, v. 24, p. 113-138.

Muller, P.J., and Suess, G., 1979, Productivity-sedimentation rate and sedimentary organic matter in the oceans — organic preservation: Deep Sea Research, v. 26A, p. 1347-1362.

Mullins, H.T., and Neumann, A.C., 1979, Carbonate slopes along open seas and seaways in the northern Bahamas, *in* Doyle, L.A., and Pilkey, O.H., eds., Geology of continental slopes; Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 27, p. 165-192.

Mutti, E., and Ricchi-Lucchi, F., 1978, Turbidites of the northern Apennines: Internatl. Geology Rev., v. 20, p. 125-166.

Nelson, C.H., 1976, Late Pleistocene and Holocene depositional trends, processes and history of Astoria deep sea fans, northeast Pacific: Marine Geology, v. 20, p. 129-173.

Nelson, C.H., Carlson, P.R., Byrne, J.V., and Alpha, T.R., 1970, Development of the Astoria canyon-fan physiography and comparison with similar systems: Marine Geology, v. 8, p. 259-291.

Nilsen, T.H., Walker, R.G., and Normark, W.R., 1980, Modern and ancient fans: Discussion: Am. Asso. Petroleum Geologists Bull., v. 64, p. 1094-1101.

Normark, W.R., 1970, Growth Patterns of Deep-Sea Fans: Am. Assoc. Petroleum Geologists Bull., v. 54, p. 2170-2195.

Normark, W.R., Hess, G.R., Stow, D.A.V., and Bowen, A.J., 1980, Sediment waves on the Monterey Fan levee: A preliminary interpretation: Marine Geology, v. 37, p. 1-18.

Olsson, R.K., Miller, K.G., and Ungrady, T.R., 1980, Late Oligocene transgression of middle Atlantic coastal plain: Geology, v. 8, p. 549-554.

Paull, C.K., and Dillon, W.P., 1980, Erosional origin of the Blake Escarpment: An alternative hypothesis: Geology, v. 8, p. 538-542.

Piper, D.J.W., and Brisco, C.D., 1975, Deep-water and continental-margin sedimentation, DSDP Leg 28, Antarctica, *in* Hayes, D.E., Frakes, L.A., et al., Initial reports of the Deep Sea Drilling Project, Vol. 28: Washington, D.C., U.S. Govt. Printing Office, p. 727-755.

Pisciotto, K.A., 1981, Distribution, thermal histories, isotopic compositions, and reflection characteristics of siliceous rocks recovered by the Deep Sea Drilling Project, *in* Warme, J.E., Douglas, R.G., and Winterer, E.L., eds., The Deep Sea Drilling Project: A decade of progress: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 32, p. 129-147.

Pitman, W.C., 1978, Relationship between eustacy and stratigraphic sequence of passive margins: Geol. Soc. America Bull., v. 89, p. 1389-1403.

Reich, V. and von Rad, U., 1979, Silica diagenesis in the Atlantic Ocean: Diagenetic potential and transformations, *in* Talwani, M., Hay, W.W., and Ryan, W.B.F., eds., Deep sea drilling results in the Atlantic Ocean continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 315-341.

Ristvet, B.L., Tremba, E.L., Couch, R.F., Fetzer, J.A., Goter, E.R., Walter, D.R., and Wendland, V.R., 1978, Geologic and geophysical investigations of the Eniwetok nuclear craters: Washington, D.C., Air Force Weapons Laboratory Report AFWL-TR-77-242, Defense Nuclear Agency, p. 1-263.

Rona, P., 1978, Plate tectonics, energy and mineral resources: Basic research leading to payoff: EOS (Am. Geophys. Union Trans.), v. 58, p. 629-639.

Roth, P.H., 1978, Cretaceous nannoplankton, biostratigraphy, and oceanography of the northwestern Atlantic Ocean, *in* Benson, W.E., and Sheridan, R.E., et al., Initial reports of the Deep Sea Drilling Project, Vol. 44: Washington, D.C., U.S. Govt. Printing Office, p. 731-759.

Rupke, N.A., 1978, Deep clastic seas, *in* Reading, H.G., ed., Sedimentary environments and facies: Oxford, England, Elsevier, p. 372-415.

Ryan, W.B.F., and Cita, M.B., 1977, Ignorance concerning episodes of oceanwide stagnation: Marine Geology, v. 23, p. 197-215.

Sayles, F.L., and Manheim, F.T., 1975, Interstitial solutions and diagenesis in deeply buried marine sediment: Results from the Deep Sea Drilling Project: Geochim. et Cosmochim. Acta, v. 39, p. 103-127.

Schlager, W., 1981, The paradox of drowned reefs and carbonate platforms: Geol. Soc. America Bull., v. 92, p. 192-211.

Schlager, W., and Ginsburg, R.N., 1981, Bahama carbonate platforms — the deep and the past: Marine Geology, v. 44, p. 1-24.

Schlanger, S.O., 1963, Subsurface geology of Eniwetok Atoll: U.S. Geol. Survey Prof. Paper 260-BB, p. 991-1038.

Schlanger, S.O., 1981, Shallow-water limestones in oceanic basins as tectonic and paleoceanographic indicators, *in* Warme, J.E, Douglas, R.G., and Winterer, E.L., eds., The Deep Sea Drilling Project: A decade of progress: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 32, p. 209-226.

Schlanger, S.O., and Douglas, R.G., 1974, The pelagic ooze-chalk-limestone transition and its implications for marine stratigraphy, *in* Hsu, K.J., and Jenkyns, H.C., eds., Pelagic sediments: On land and under the sea, Spec. Pub. Internatl. Assoc. Sedimentologists, Vol 1: Oxford, England, Blackwell, p. 117-148.

Schlanger, S.O., Jackson, E.D., et al., 1976, Initial reports of the Deep Sea Drilling Project, Vol. 33: Washington, D.C., U.S. Govt. Printing Office, 973 p.

Schlanger, S.O., and Jenkyns, J.C., 1976, Cretaceous oceanic anoxic events: Causes and consequences: Geologie en Mijnbouw, v. 55, p. 179-184.

Schlanger, S.O., and Premoli-Silva, L., 1981, Tectonic, volcanic and paleogeographic implications of redeposited reef faunas of Late Cretaceous and Tertiary age from the Nauru Basin and the Line Islands, *in* Larson, R.L., Schlanger, S.O., et al., Initial reports of the Deep Sea Drilling Project, Vol. 61: Washington, D.C., U.S. Govt. Printing Office, p. 817-828.

Scholle, P.A., 1977, Chalk diagenesis and its relation to petroleum exploration: Oil from chalks, a modern miracle? Am. Assoc. Petroleum Geologists Bull., v. 61, p. 982-1009.

Scholle, P.A. and Arthur, M.A., 1980, Carbon isotopic fluctuations in pelagic limestones: Potential stratigraphic and petroleum exploration tool: Am. Assoc. Petroleum Geologists Bull., v. 64, p. 67-87.

Sheldon, R.P., 1981, Ancient marine phosphorites: Ann. Rev. Earth and Planet. Sci., v. 9, p. 251-284.

Sheldon, R.P., and Burnett, W.C., 1980, Fertilizer mineral potential in Asia and the Pacific: Proc. of Fertilizer Raw Materials Resources workshop, August 1979, Honolulu, Hawaii, East-West Resource Systems Inst., 477 p.

Shepard, F.P., and Dill, R.F., 1966, Submarine canyons and other sea valleys: Chicago, Rand McNally, 381 p.

Sheridan, R.E., and Enos, P., 1979, Stratigraphic evolution of the Blake Plateau after a decade of scientific drilling, *in* Talwani, M., Hay, W.W. and Ryan, W.B.F., eds., Deep drilling results in the Atlantic Ocean: Continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 109-122.

Shipley, T.H., Buffler, R.T., and Watkins, J.S., 1978, Seismic stratigraphy and geological history of Blake Plateau and adjacent western Atlantic continental margin: Am. Assoc. Petroleum Geologists Bull., v. 62, p. 792-812.

Southam, J.R., and Hay, W.W., 1981, Global sedimentary mass balance and sea level changes, *in* Emiliani, C., ed., The Sea, Vol. 7: New York, John Wiley, p. 1617-1684.

Stanley, D.J., and Kelling, G., eds., 1978, Sedimentation in submarine canyons, fans and trenches: Stroudsburg, PA, Dowden, Hutchinson and Ross, 382 p.

Stow, D.A.V., 1981, Laurentian Fan: Morphology, sediments, processes, and growth pattern: Am. Assoc. Petroleum Geologists Bull., v. 65, p. 375-393.

Stow, D.A.V., and Lovell, J.P.B., 1979, Contourites: Their recognition in modern and ancient sediments: Earth Sci. Rev., v. 14, p. 251-291.

Thiede, J., and van Andel, T.H., 1977, The paleoenvironment of anaerobic sediments in the Late Mesozoic South Atlantic Ocean: Earth and Planet. Sci. Letters, v. 33, p. 301-309.

Thierstein, H.R., and Berger, W.H., 1978, Injection events in earth history: Nature, v. 276, p. 461-464.

Tissot, B., Demaison, G., Mason, P, Delteil, J.R., and Combaz, A., 1980, Paleoenvironment and petroleum potential of middle Cretaceous black shales in Atlantic basins: Am. Assoc. Petroleum Geologists Bull., v. 64, p. 2051-2063.

Tissot, B., Durand, B., Espitalie, J., and Combaz, A., 1974, Influence of nature and diagenesis of organic matter in formation of petroleum: Am. Assoc. Petroleum Geologists Bull., v. 58, p. 499-506.

Tucholke, B.E., 1981, Geological significance of seismic reflectors in the deep western North Atlantic Basin, *in* Warme, J.E., Douglas, R.G., and Winterer, E.L., eds., The Deep Sea Drilling Project: A decade of progress: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 32, p. 23-37.

Tucholke, B.E., and Mountain, G.S., 1979, Seismic stratigraphy, lithostratigraphy and paleosedimentation patterns in the North American Basin, *in* Talwani, M., Hay, W.W., and Ryan, W.B.F., eds., Deep drilling results in the Atlantic Ocean: Continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 58-86.

Vail, P.R., Mitchum, R.M., Jr., Shipley, T.H., and Buffler, R.T., 1980, Unconformities of the North Atlantic: Philos. Trans. Royal Soc., v. 294, p. 137-155.

Vail, P.R., Mitchum, R.M., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level, part 3: Relative changes of sea level from coastal onlap, *in* Payton, C., ed., Seismic stratigraphy — applications to hydrocarbon exploration: Am. Assoc. Petroleum Geologists Mem. 26, p. 63-81.

Veizer, J., and Fritz, P., 1976, Possible control of post-depositional alteration in oxygen paleotemperature determinations: Earth and Planet. Sci. Letters, v. 33, p. 226-260.

Veizer, J., Holser, W.T., and Wilgus, C.K., 1980, Correlation of $^{13}C/^{12}C$ and $^{34}S/^{32}S$ secular variations: Geochim. et Cosmochim. Acta, v. 44, p. 579-587.

Walker, R.G., 1976, Turbidites and associated coarse clastic deposits: Geosci. Canada, v. 3, p.25-36.

Weissert, H., McKenzie, J., and Hochuli, P., 1979, Cyclic anoxic events in the Early Cretaceous Tethys Ocean: Geology, v. 7, p. 147-152.

White, S.M., Chamley, H., Curtis, D., Klein, G., Mizuno, A., 1980, Sediment synthesis: Deep Sea Drilling Project Leg 58, Phillipine Sea: *in* deVries Klein, G., Kobayashi, K., et al., Initial reports of the Deep Sea Drilling Project, Vol. 58: Washington, D.C., U.S. Government Printing Office, p. 963-1013.

Wilde, P., Normark, W.R., and Chase, T.F., 1980, Potential petroleum reservoirs on deep-sea fans off central California: Am. Assoc. Petroleum Geologists Bull., v. 64, p. 803.

Wright, L.D., and Coleman, J.M., 1973, Variations in morphology of major river deltas as functions of ocean wave and river discharge regimes: Am. Assoc. Petroleum Geologists Bull., v. 57, p. 370-398.

CAUSES OF LONG-TERM CHANGES IN THE ATMOSPHERE, OCEANS, CRYOSPHERE, BIOSPHERE, AND MAGNETIC FIELD

A. INTRODUCTION

The enormous progress in our understanding of the evolution of the oceans, climate, marine biota, and the history of the earth's magnetic field in the past 14 years can be attributed in large part to the results obtained from ocean drilling and the Deep Sea Drilling Project. Initial phases of the DSDP focused on geophysical objectives, but since the early 1970's a merger of geophysical, geochemical, and paleontological approaches and concepts have contributed to a far reaching study of ocean paleoenvironment, paleoceanography, and paleoclimatology. The results accumulated over a decade of effort constitute a "paleoceanographic inventory" of the major trends and events in the history of circulation, changes in geochemical balance, and biologic and climatic evolution during the past 150 m.y. of earth history (Berger, 1979). Important contributions to the paleoceanographic inventory have been the development of global stratigraphies based on fossil plankton, magnetic reversals, stable isotopes, and the paleogeographies of continents and oceans reconstructed from linear magnetic anomalies on the seafloor. Together they have provided the necessary definition of time and space within which the changes in ocean paleoenvironment and climate can be considered.

The response time of the climate and oceans to environmental change is much shorter than the resolution of the stratigraphies obtainable in most sections recovered by rotary drilling. Thus the research of the past decade has been limited to an examination of the long-term change in ocean and climate and to educated guesses as to their interrelationships, detailed history, and mechanism of change. A major step forward occurred during the current phase of deep-ocean drilling with the development of the hydraulic piston core and high resolution stratigraphies of pre-Pleistocene sediments. It is now possible to describe not only the general trends but the detailed sequences of ocean and biotic changes in sediment cores. This development has greatly enhanced our ability to relate sequences from different portions of the ocean and to understand the mechanisms which cause change in ocean-climate systems. In one step, it has become possible to link the researches of the Quaternary, which examine environmental response of the ocean to orbital and other short-term (less than 10^6 yr) effects, to the researches of the Cenozoic and Mesozoic, and the study of long-term ocean response (greater than 10^6 yr).

The scientific approach to the study of paleoenvironments and the long term evolution of the atmosphere, ocean, cryosphere system has been largely inductive, in that observations have been used to develop plausible explanations of the record. For the most part geologic data from the pre-Neogene are inadequate to fully understand the nature of the record. This is because of a lack of global sample coverage and also because we are dependent on proxy indicators of paleoenvironmental conditions. Recently a second, more deductive type of scientific approach has become useful in identifying important mechanisms and in producing hypotheses which may be tested by additional drilling. In the deductive approach, a set of physical laws is assumed to govern the climate or oceanic system. The model is a mathematical representation of the physical processes thought to be important in governing the system under consideration. By performing a series of sensitivity studies, perturbing the model by making a change in some boundary condition (e.g., a change in equator-to-pole ocean temperature gradient in an atmospheric model), models can provide a firmer physical basis for interpreting the significance of different geologic variables. Most importantly, mathematical models may be used to develop physically plausible hypotheses which can be directly tested by additional ocean drilling designed to achieve comparison with the geologic record.

The combined approach of mathematical modeling and collection of data which directly tests hypotheses has significant potential to isolate important mechanisms and to greatly increase our physical understanding of the atmosphere, ocean, cryosphere, lithosphere system. We view it as one of the exciting new approaches to ocean paleoenvironment and paleoclimatology research in the post-1983 drilling program.

In this paper we propose a program for scientific ocean drilling that addresses a broad range of objectives related to the evolution of the ocean, global climate, marine biota, and the history of the earth's magnetic field and the mechanisms of change within these systems.

Our program is the result of the joint efforts of the members of the Conference on Scientific Ocean Drilling (COSOD), Working Group IV (W.G. IV), the JOIDES Ocean Paleoenvironmental Panel (OPP) and a number of other dedicated scientists. Prior to the COSOD meeting in Austin, Texas, the two panels independently prepared white papers outlining a science proposal for the post-1983 program of ocean drilling. Subsequently the two papers were found to contain similar science proposals and were combined. The revised white paper presented herein was prepared by Nicholas J. Shackleton, Chairman W. G. IV, Robert Douglas, Chairman OPP, and James Hays, T. C. Moore, Jr., Dennis Kent, Garrett Brass, and Eric Barron.

Our concern is with the history of ocean circulation, ocean chemistry, and the organisms in the oceans of the past. This history will provide us with a much greater appreciation for, and understanding of, the various interactions which take place between the land, the oceans, the ice sheets, and the atmosphere, and the impact of these interactions on the biota. First, such a history of long-term change will provide information on the range of possible conditions, both in terms of mean states and their associated variability. Second, the history and character of past environmental conditions have had a profound influence on the history of biotic evolution on this planet; it is important to be able to determine relationships between the Earth's systems and their interactions with the biosphere as all evolve. Finally, the interactions between different parts of the Earth's systems can be best understood by examining their relationships during times of change. It is particularly important that we understand the relationships of patterns of oceanic deep and surface circulation with the global and regional budgets of the chemical and biogenic components in sediments. The atmosphere is removed by one step from the sediments beneath the ocean. However, the history of world climate is stored in the sediments quietly accumulating on the sea floor.

B. LONG-TERM CHANGES IN THE OCEAN AND ATMOSPHERE

B.1 Mesozoic Ocean

Jurassic Superocean. The globe 160 m.y. ago can be divided into a supercontinent surrounded by a single superocean. This ocean extended from pole to pole and around more than half of the earth's circumference. By mid-Jurassic time, spreading developed a large triangular reentrant in the eastern part of the continent, Tethys, which ultimately opened to the west and created a seaway that permitted circulation.

Sediment sequences of this age are well known from the early Atlantic and Tethys both from land sections and from DSDP sites, but these have to be considered marginal sea deposits in a predominantly continental setting. We have virtually no information about the Jurassic superocean. Most of the sea floor of that time has been subducted, but isolated areas are available for drilling in the western Pacific, the Arctic, and northeast of the Weddell Sea (Fig. 1). These locations cover both low and high paleolatitudes.

We seek to increase our understanding of the ocean state, circulation, and climate of the Jurassic superocean, to compare it to the history of development of the Atlantic Ocean, and to determine the effects that the opening of the mid-American gateway in the late Jurassic had on the superocean, the Tethys seaway, and marginal seas.

Hypsography of the Mesozoic Ocean. Paleogeographic reconstructions generally give the impression that the Mesozoic superocean, the ancestor of the present Pacific Ocean, was in a bathymetric sense dominated by elevated mid-ocean ridge crests and subsiding lithospheric plates.

Since World War II bathymetric charting, dredging, and both atoll and DSDP drilling have confirmed the ideas of widespread Mesozoic volcanism in the Pacific followed by large-scale subsidence. We now know that major bathymetric features, such as the Mid-Pacific Mountains and at least the northern Marshall Islands, were high, vegetated volcanic islands, fringed by reefs in early Cretaceous time. The Line Islands were the sites of Cretaceous reef growth. Cretaceous reef fossils have been dredged from subsided seamounts and guyots over an area that extends from the northern Line Islands to the Japan Trench (Fig. 2a). These Mesozoic volcanic island groups now lie on the Pacific Plate. However, remnant oceanic plateaus, such as the Nicoya Complex now exposed as an allochthonous terrane in Central America, attest to the fact that the Farallon Plate bore volcanic islands. It is probable that the Kula and Phoenix plates were also marked by volcanic islands attributable to mid-plate volcanism (Fig. 2b).

These Mesozoic bathymetric features must surely have affected the oceanography of the superocean. Patterns of both the bottom and surface circulation must have been complex. A wide range of ecologic niches for both shallow- and deep-water faunal colonization were available as were numerous "stepping

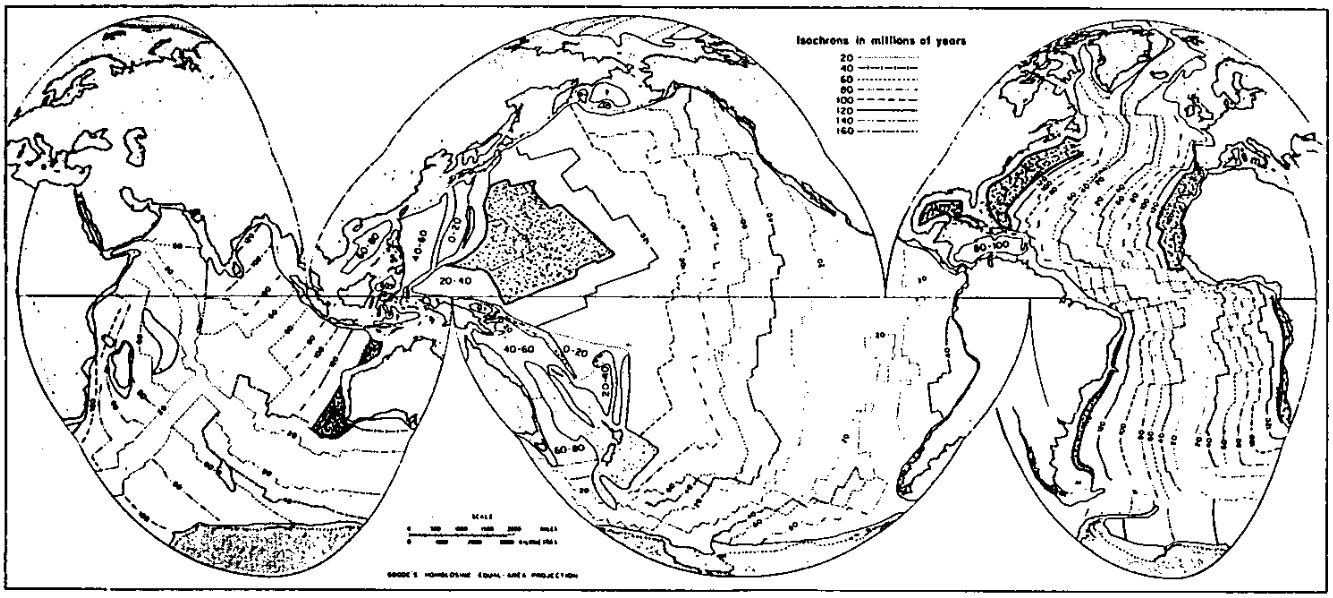


Figure 1. Schematic crustal age map. Ages based on data from magnetic anomalies (Berger and Winterer, 1974). Most of the pre-140 m.y. section has been subducted, but isolated areas are available for drilling in the western Pacific, eastern Indian, and north Atlantic oceans.

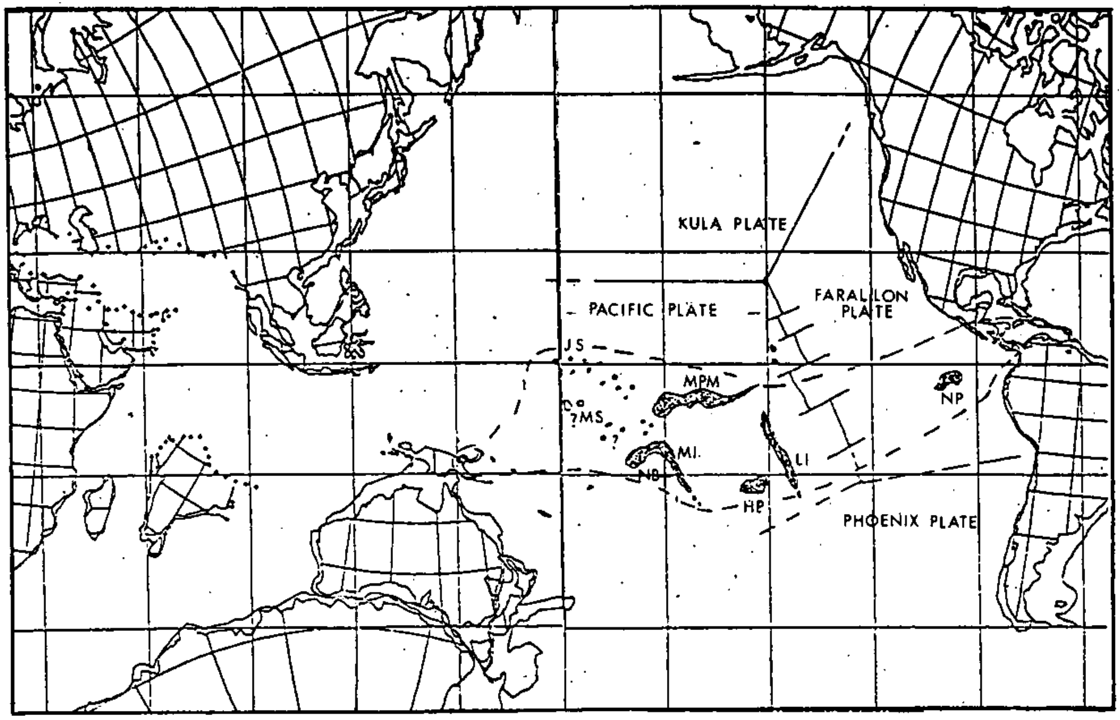


Figure 2a. Mesozoic mountain ranges, plateaus, and reef-bearing seamount provinces in the Cretaceous (80 m.y.B.P.) ocean. NP = Nicoya Plateau, LI = Line Islands, MP = Manihiki Plateau, MI = Marshall Islands, NB = Nauru Basin, MPM = Mid-Pacific Mountains, JS = Japan-Wake Seamounts, MS = Magellan Seamounts. Dashed line encloses "stepping stone" province across which reef faunas migrated. Base map from Smith and Briden (1977). Geology modified from Schlanger et al. (1981).

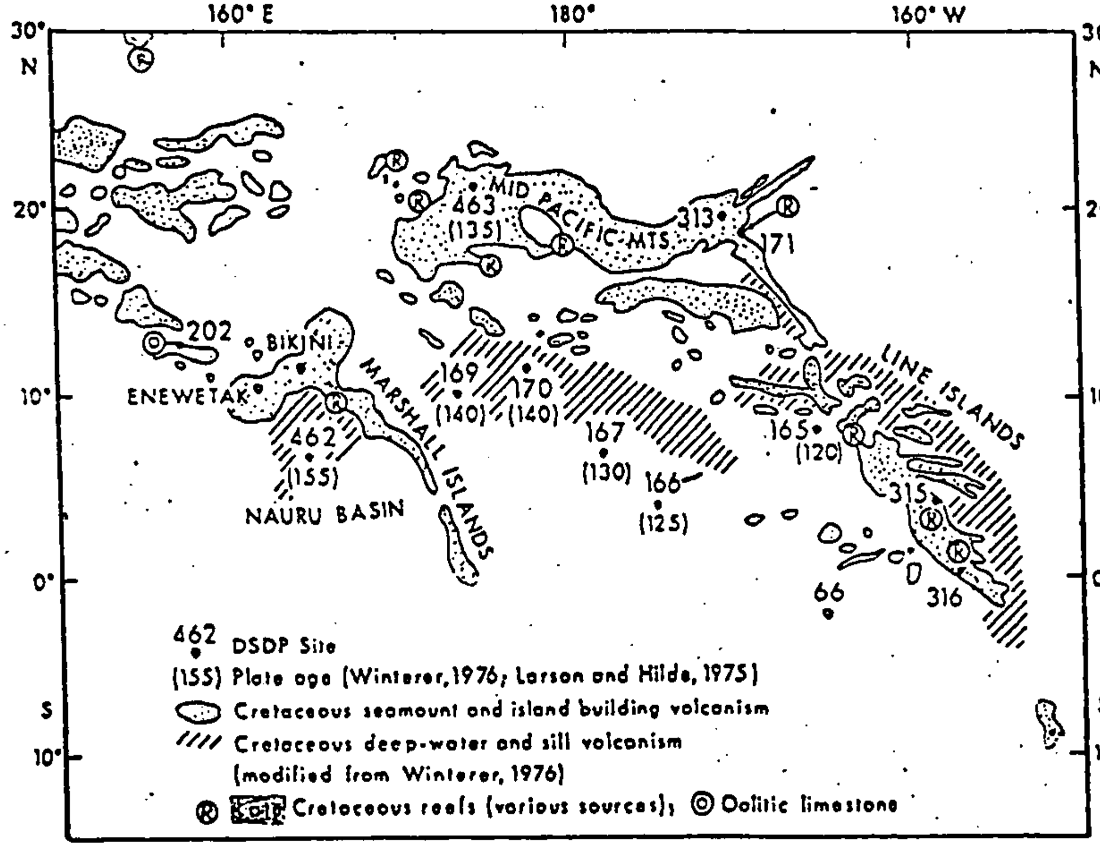


Figure 2b. Distribution of Cretaceous mid-plate volcanics and rocks during the interval 115-70 m.y.B.P. on the Pacific Plate. (from Schlanger and Premoli-Silva, 1981; modified from Winterer, 1976).

stones" for the spread of shallow-water benthic organisms. The enormous volcanic and hydrothermal activity in the Cretaceous may have influenced the chemistry of the sea water. The abundance of airborne ash found in Mesozoic sediments of the Pacific Basin suggests a high dust level that may have had an effect on the climate of the period. Further, the effect of mid-plate volcanism on bathymetry is not restricted to edifice-building; reheating of old lithosphere during widespread volcanism would have caused regional uplift of the ocean basin and contributed to major Mesozoic transgressions. We need to develop models to account for mid-plate volcanism because the wide temporal and geographic extent of western Pacific mid-plate volcanism must have influenced the bathymetric evolution of the region. It has been suggested by a number of workers that the subsidence path of a large portion of the Pacific oceanic lithosphere has diverged significantly from an ideal Parsons-Sclater curve due to reheating of the lithosphere subsequent to its formation at ridge crest (Figs. 3a, 3b). We need to quantify the vertical component of plate motion due to this reheating effect and to determine the temporal and spatial extent of bathymetric highs associated with thermally induced uplift and volcanic edifices.

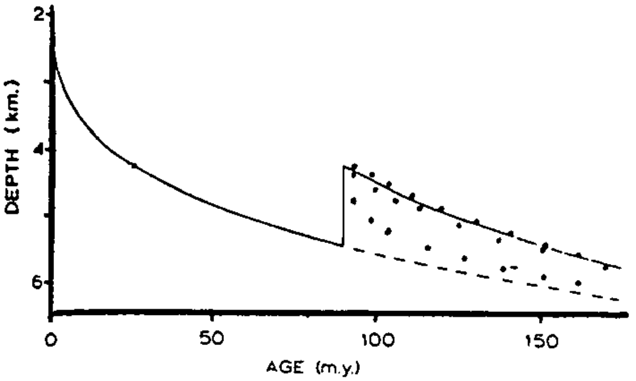


Figure 3b. Swell subsidence after reheating at 90 m.y.B.P. Dashed line is expected subsidence without reheating, solid line is expected subsidence of normal 24 m.y.-old lithosphere. Symbols show how reheated lithosphere would subside if given the geotherm in Figure 3a which is labelled with the same symbol. The open circles will not match the observed swell subsidence (from Crough, 1978).

The global, Cretaceous rise in sea level and transgression has been ascribed to changes in the volume of the mid-ocean ridge systems caused by changes in spreading rates. We need to drill through Jurassic oceanic sections in order to verify changes in spreading rates. Further, some workers consider mid-plate uplift that accompanies volcanism to be a contributing factor to the Cretaceous transgressions. By extending our knowledge of the geographic extent and chronology of mid-plate volcanism, we may be able to define the contribution of off-ridge volcanism to the great Cretaceous transgressions. We need to reexamine several facets of Mesozoic paleobathymetry:

1. Is Mesozoic bathymetry accurately described by the Parsons-Sclater age/depth relationship, or were large areas of the sea floor re-elevated, particularly in Cretaceous time, in the Pacific Basin?

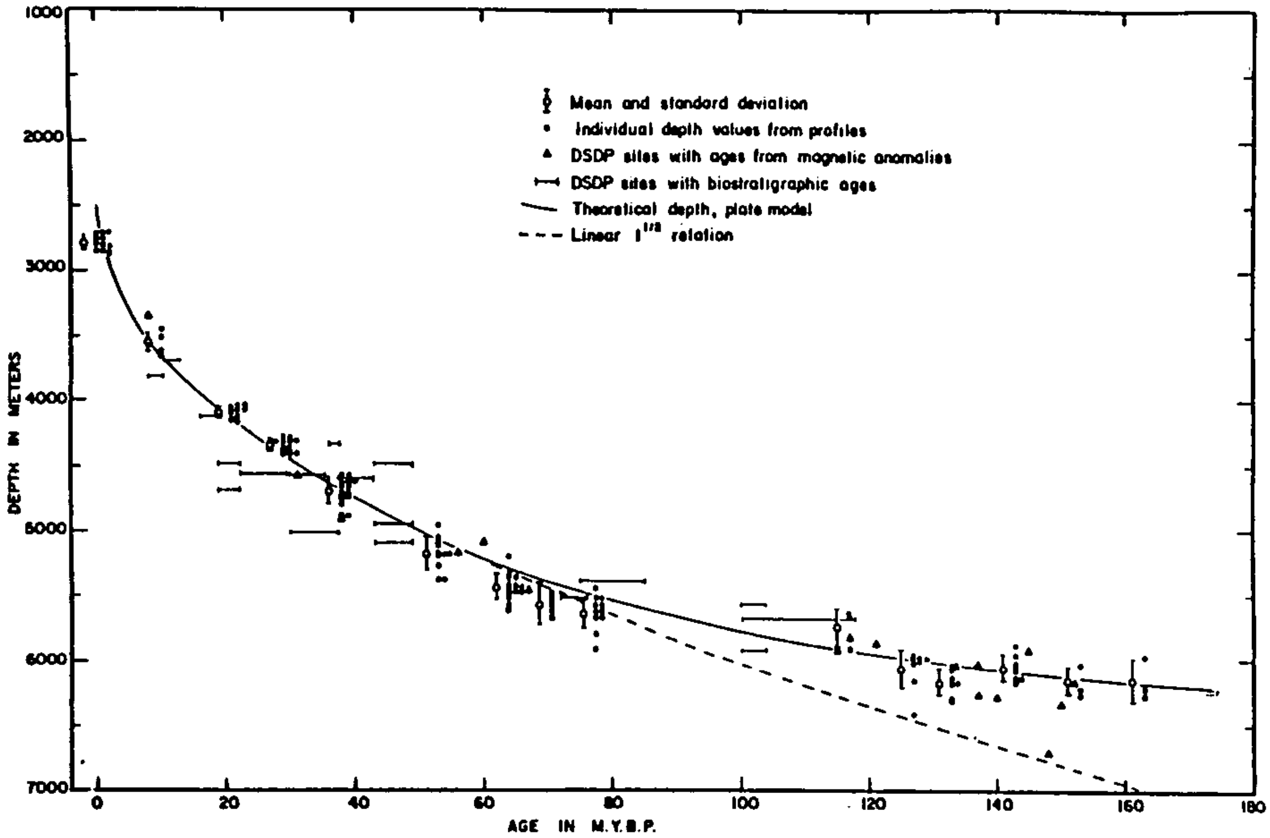


Figure 3a. Age/depth relationship for Pacific lithospheric plate (from Parsons and Sclater, 1977).

2. Are interpretations of the levels of the Mesozoic calcium carbonate compensation depth (CCD) correct? Most CCD interpretations are based on the assumption that the ocean floor subsided according to the Parsons-Sclater curve. If there have been significant departures from this curve then Mesozoic CCD data must be reinterpreted.
3. The overall extent and duration of Cretaceous mid-plate, and indeed continental, volcanism suggests that volcanic contributions such as water vapor, CO_2, and dust may have affected the Cretaceous climatic regimes. In many Cretaceous climatic modeling efforts major volcanism has not been included as a parameter.

Sea Level and Oceanic Climate in the Mesozoic. A large body of descriptive data based mainly on fossils and sediment type supports the idea that the global climate of the Cretaceous and Jurassic was warm and equable with low thermal gradients across latitude and relatively homogeneous vertical oceanic thermal structure. Such an ocean-climate state has been ascribed to the effects of a latitudinal pattern of oceanic circulation, ice-free poles, high eustatic sea level, and ocean-continent geography.

Quantitative paleoclimatic data, while generally supportive of the "warm and equable" climate model, suggest a more complex picture. Oxygen isotope analyses of benthic foraminifera, which have been a major approach in understanding ocean-climate states in the Cenozoic, are limited to the post-Santonian with a scatter of data points in the Early and mid-Cretaceous (Douglas and Savin, 1975; unpublished data) (Figs. 4a, 4b). The isotopic temperatures are open to reinterpretation if considerable salinity contrast existed in the Cretaceous ocean; for example, if shallow seas and restricted ocean basins were major sources of warm, highly saline intermediate or deep water; (Roth, 1978; Brass et al., 1980). In that case, the record may show the effects of regional patterns of precipitation and evaporation as well as temperature.

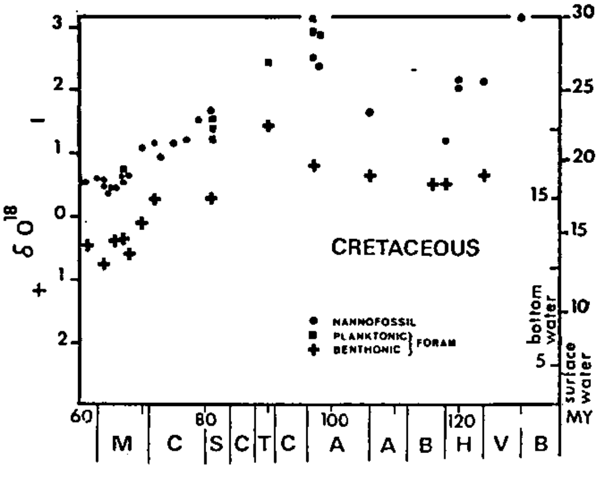


Figure 4a. Oxygen isotope analyses of foraminifera and calcareous nannofossils from DSDP Sites 47, 49, 50, 305, and 306 (Douglas and Savin, 1975; unpublished data). Paleotemperature scale assumes ice-free poles and a salinity distribution similar to the present-day ocean.

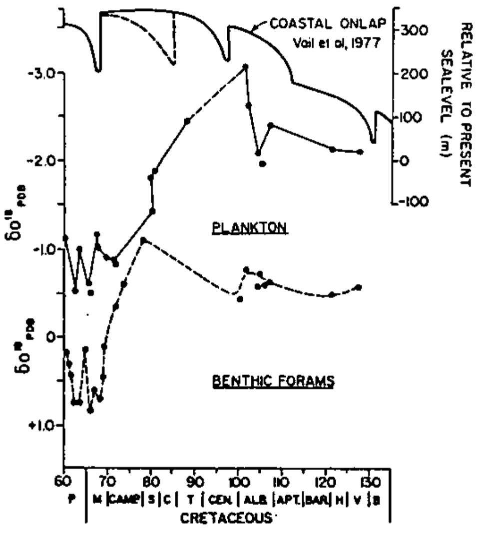


Figure 4b. Comparison of oxygen isotope analyses to variation in sea level. Sea level data from Vail et al., 1977; isotopic data from Figure 4a. (Douglas and Savin, 1975; unpublished data).

A mechanism which is frequently evoked to explain equable Mesozoic climate-ocean states is a high stand of eustatic sea level. Comparison of the benthic foraminiferal oxygen-isotope record and quantitative estimates of fluctuation of sea level (Vail and Hardenbol, 1979) suggests that changes in land-sea relationship were a major modulator of climate in the Cenozoic (Berger et al., 1981). When probable ice-volume effects for the Oligocene and post-mid Miocene are taken into account, the correlation is impressive (Figs. 5a, 5b; Douglas and Savin, 1982). Simulation experiments with climate models also suggest that albedo changes due to change in land geography offer a viable explanation of presumed Cretaceous climates (Thompson and Barron, 1981; Barron et al, 1981). However, there are important outstanding questions as to the mechanisms which control eustatic change (Pitman, 1978) and whether or not changes in

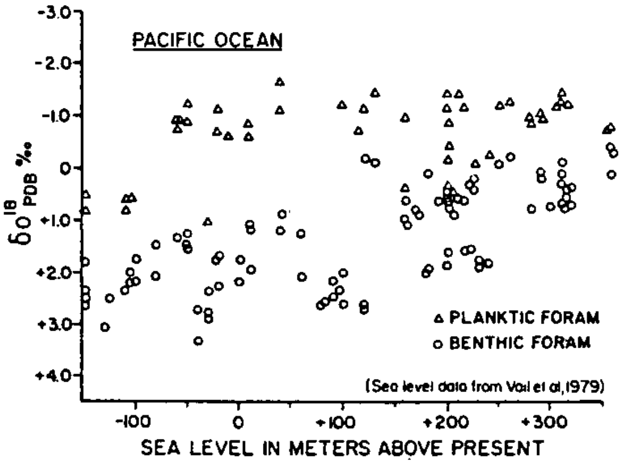


Figure 5a. Oxygen isotope analyses of benthic and planktic foraminifera, based on DSDP cores, plotted according to sea level for the Cenozoic based on Vail et al. (1977). (from Douglas and Savin, 1982).

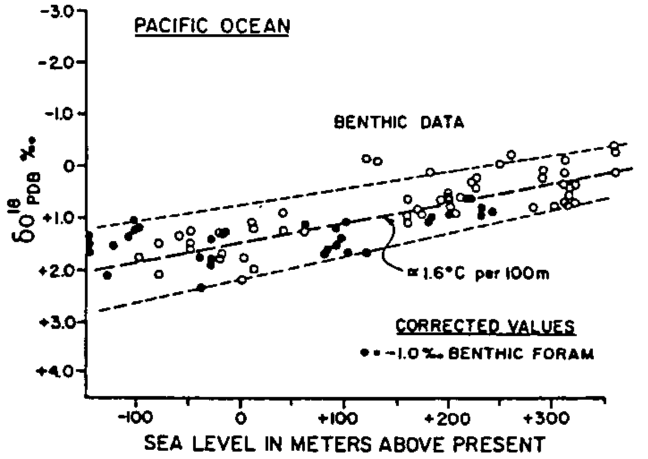


Figure 5b. Same isotopic data as in Figure 5a corrected for probable ice-volume effects in the Oligocene and post-middle Miocene. Ice-volume was assumed to be approximately equal to that of the latest Pleistocene and equivalent to a one per mil change in the isotopic composition of sea water. (from Douglas and Savin, 1982).

sea level in the Cretaceous were globally synchronous (Morner, 1981). Morner (1980; 1981) suggests that eustacy results from paleogeoid and tectonic changes and is, thus, regional in character.

Several types of problems concern the understanding of the relationship between Cretaceous climate and ocean state and the effect of eustacy:

- Is there a cause-effect relationship between the stand of sea level and climate-ocean conditions in the Mesozoic?
- Were polar regions sites of early glaciation and/or significant ice build-up?
- What were the latitudinal and vertical thermal gradients in the Mesozoic ocean?
- When did the cooling trend in the Cretaceous begin and what triggered the change?
- How did the development of meridional seaways such as the South Atlantic and Indian oceans effect the thermal structure of the ocean?

Finally, it is essential for all studies of the Mesozoic ocean that we have a good, open-ocean biostratigraphy with magnetostratigraphy and considerably more age calibration than is presently available. Without these, any attempts to determine rates of change and to calculate geochemical budgets will be impossible.

In order to attack the problems of paleoceanography, climate, and geochemical cycling that we have outlined in the Cretaceous and Jurassic, it will be necessary to expand the present sample coverage (including sites which will be drilled in the 1981-83 program) to include high-latitude regions and better recovery in the early Mesozoic. We need to define the climatic history of the late Mesozoic in low and high latitude, to determine the vertical ocean gradients in key regions of the ocean, and to develop an improved stratigraphy which will facilitate detailed comparisons of inter-ocean basins. To accomplish these goals, we propose drilling the thick sequences of sediment primarily found on aseismic ridges. This drilling will be facilitated by improved through-the-bit coring techniques and will overcome past problems related to coring sequences of carbonate and chert.

B.2 Ocean Circulation

Formation and Circulation of Deep Water. The history of formation of deep water and bottom water is an important problem to paleoclimatology and ocean circulation. Most of the heat in the earth's fluid envelope is stored in the waters of the deep ocean. Conversely the deep circulation of the ocean is, in large part, a response to the requirements of the earth's heat transport regime. Studies in DSDP cores of oxygen and carbon isotopes, benthic foraminifera and ostracods, and sedimentological indicators are beginning to provide the necessary tools to decipher the past.

Deep circulation in the modern ocean is dominated by cold waters formed in polar regions. Oxygen isotope evidence and deep-sea benthic faunal data (Benson, 1975; Douglas and Woodruff, 1981) suggest that prior to the Oligocene, ocean bottom waters were warmer and the pattern of thermohaline circulation was probably different. Since the Miocene, the major changes in formation and circulation of deep water have been associated with the development of polar ice, with the most significant changes occurring in the mid-Miocene. Core-to-core differences in the oxygen-isotope composition of benthic foraminifera of the same age appear related to changes in deep-water properties from region to region. Studies of the Miocene ocean indicate that there were small regional differences in the thermal structure of deep water but that the vertical thermal gradients in the early and middle Miocene were quite different than in the late Miocene, Pliocene, and at present (Savin et al., 1981) (Figs. 6a, 6b). The changes in the thermal structure of the Miocene ocean are associated with regional variations in the intensity of dissolution of calcium carbonate (Van Andel et al., 1975; Davies and Worsley, 1981) and the development of widespread hiatuses in the ocean. In turn, all these are closely correlated with an increase in Antarctic ice between 16.5 and 14.0 m.y.B.P. and, again at 9 m.y.B.P. However, it remains unclear what initiated the growth of ice in the southern hemisphere, and when the process began.

Under conditions of warm, equable climate, a low meridional thermal gradient, and a relatively homogeneous vertical oceanic thermal structure, warm, saline waters formed by evaporation in epicontinental seas may have been an important source of intermediate and deep waters in the ocean. Thus in the early Tertiary, and particularly in the Mesozoic, formation and circulation of deep water may have been driven by salinity variations produced in low latitudes (Roth, 1978; Brass et al., 1982). This idea is supported by recent model simulations of mid-Cretaceous climates which indicate that zones of high evaporation would be located along the margins of the Atlantic and Tethys (Barron and Washington, 1982) (Fig. 7). The Cretaceous may have been characterized by numerous sources of warm, saline bottom waters which would result in a complex thermohaline circulation. Such a

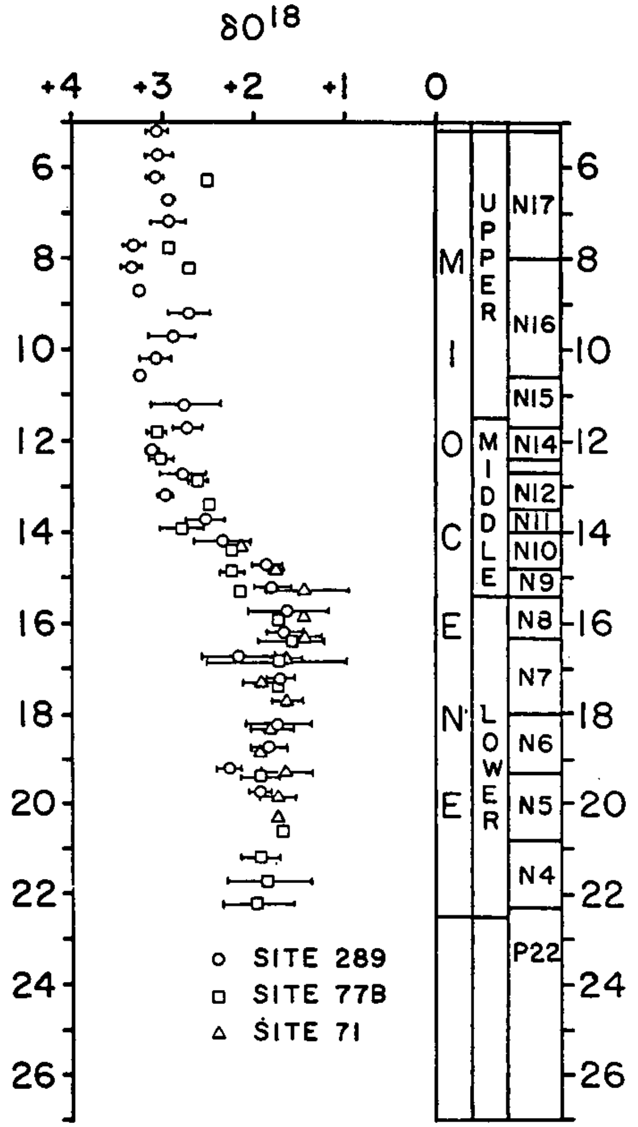


Figure 6a. Mean values and standard deviations of δO^{18} for benthic foraminifera from Sites 71, 77B, and 289, averaged over 0.5 m.y. time intervals. δO^{18} values have been adjusted to compensate for disequilibrium isotope fractionations.

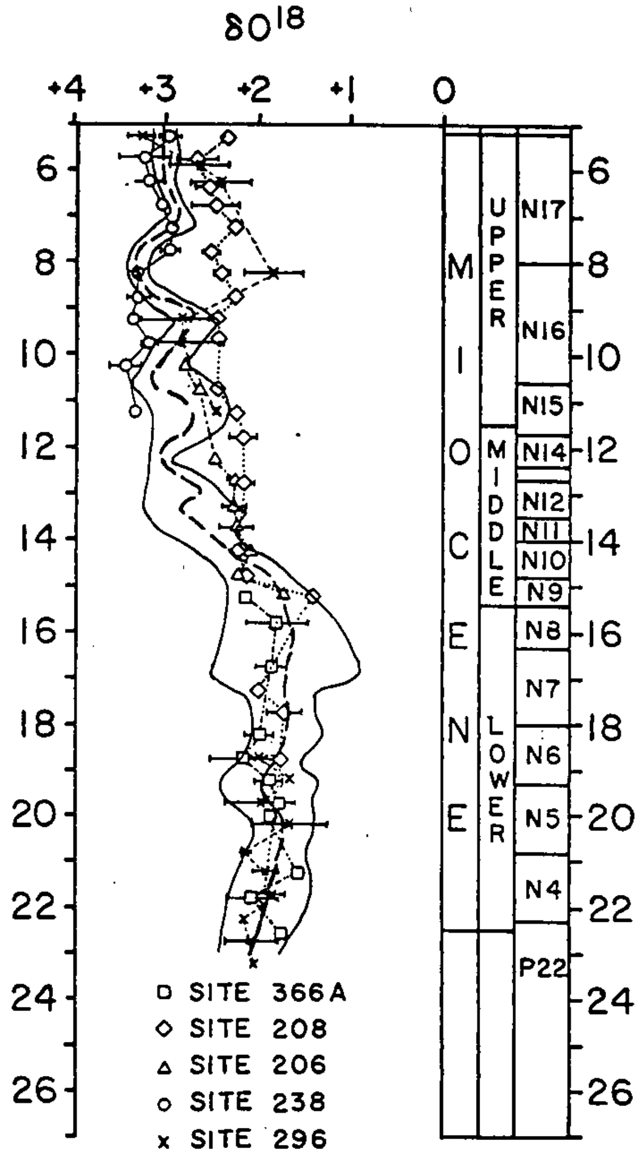


Figure 6b. Mean values and standard deviations of benthic foraminifera from Sites 206, 208, 238, 296, and 366A, averaged over 0.5 m.y. time intervals. δO^{18} values have been adjusted to compensate for disequilibrium isotope fractionations. Superimposed upon this figure are visual, best-fit curves through the mean δO^{18} values of the equatorial Pacific sites in Figure 3 (heavy dashed curve) and an envelope about the standard deviations shown in Figure 9.

model of deep circulation suggests that the distribution of temperature, salinity, and oxygen, the preservation of organic matter, and other geochemical variables which are recorded in the sediments need not to have been globally uniform. This is in contrast to the hypothesis of oceanwide stagnation in the Cretaceous. The model can be tested by drilling designed to achieve a detailed stratigraphic comparison of the record of black shales in the deep sea and continental margins and through collection of isotopic data from individual ocean basins at various paleodepths.

The process of formation and circulation of deep water in the early Tertiary and Mesozoic, whether by cold, polar-derived waters or by warm, subtropical evaporative waters, has significant geological implications and ranks as a major question in paleoceanography.

Gateways and Oceanic Circulation. Gateways are relatively narrow passages that control circulation of surface or deep water. They are important in changing both the distribution of surface water masses and the vertical structure of the oceans. Changes in interbasinal connections within or between oceans change circulation patterns and, thus, control the interregional transfer of heat and other properties (e.g., chemical). As heat transfer affects climate, gateways are ultimately a source of climatic change. The history of oceanic gateways is closely related to the long-term changes in the ocean and the evolution of climatic states. Important gateways include openings between continental blocks which can affect either

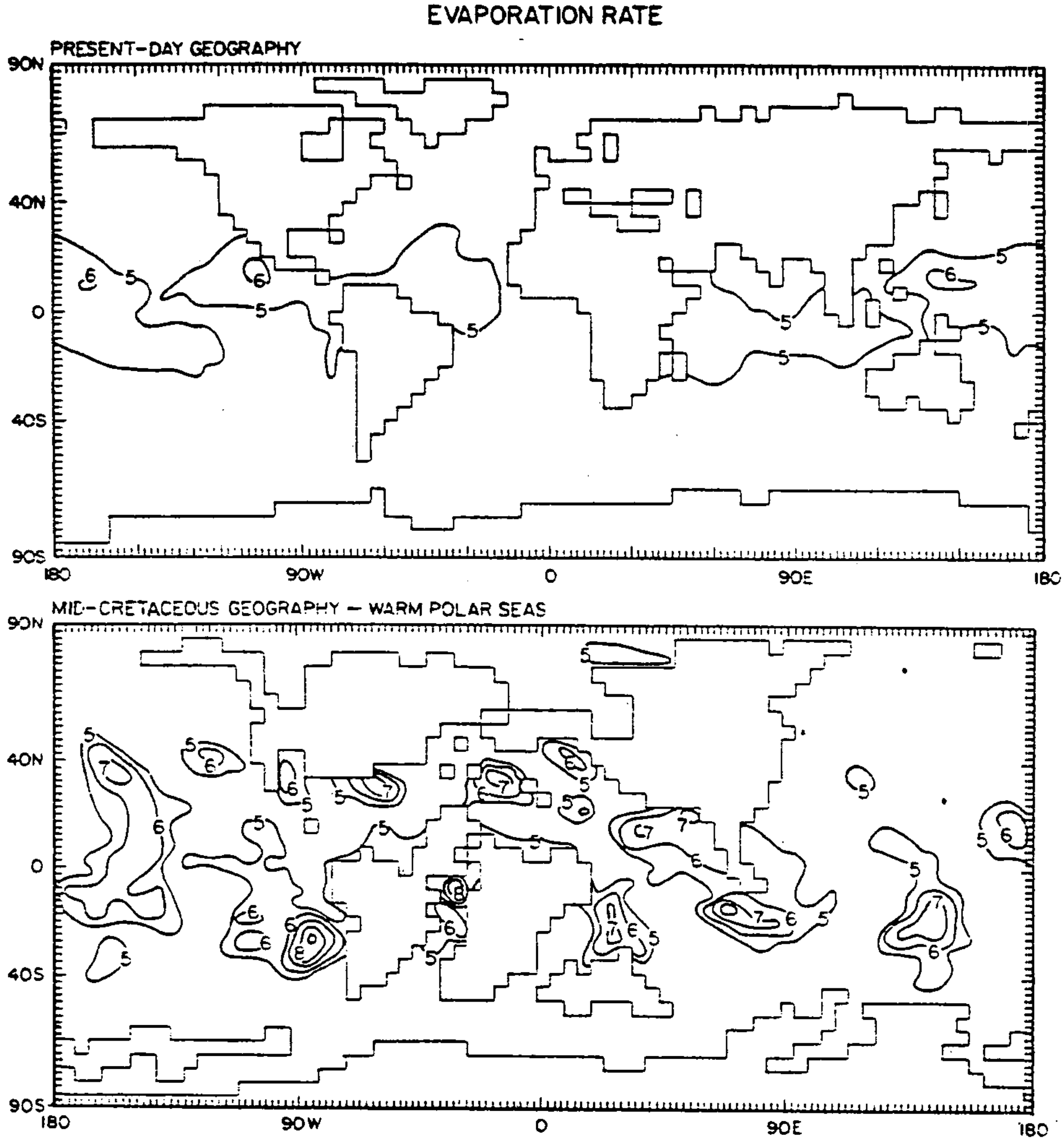


Figure 7. A comparison of the mean (30-day average) rate of evaporation in cm/day x 10^{-1} for a March present-day control simulation and a March mid-Cretaceous experiment with warm polar seas. The contour interval is 100 cm/day x 10^{-1} and only values exceeding 0.5 cm/day are given. (Barron and Washington, 1982).

the entire water column (e.g., Tasman Seaway) or only near-surface waters (e.g., the Indo-Pacific passage) and deep topographic features, such as mid-ocean ridges or aseismic ridges, which affect the flow of deep and intermediate waters (e.g., Walvis Ridge). Channels for interbasinal flow of deeper oceanic waters are usually related to fracture zones through the mid-ocean ridge systems, while those through aseismic ridges are often related to critical episodes in their subsidence history. The Vema Channel, a major conduit of the flow of Antarctic bottom water to the northwest Atlantic basins, subsided below 4,000 meters near the beginning of the Cenozoic, and has long influenced the flow of deep water in this region. Nevertheless, since the upper surface of certain bottom waters probably has never been much shallower than about 4,500 meters (e.g., Antarctic Bottom Water) a channel at 4,000 meters will have a blocking effect.

Drilled sections have been and need to be placed at strategic locations both within and near the ends of such conduits to examine the history of the flow of bottom water as recorded in the sediments.

The paleoceanographic effects of changes at gateways, their deepening or restriction, are best studied on either side and, particularly, downstream from the passage, where sediments accumulate even during phases of strong circulation. Studies must be based on transects downstream in the depositional lee of the gate — one transect for disturbances in the horizontal gradients, a second to define changes in the vertical gradients.

The closing of gateways leads to fractionation of waters between oceans and differing geochemical and sedimentary regimes. Resulting oceanic isolation can also lead to increasing biogeographic provincialism. Because geochemical, sedimentary, and biogeographic parameters are sensitive to the degree of interchange between oceans, they are good monitors of any such changes.

Specific questions that relate the paleoceanographic change to changes in oceanic gateways are objectives for deep drilling:

- What is the history of the Drake Passage Gateway? When was circum-Antarctic circulation established? Late Eocene or Oligocene? (requires drilling at high southern latitudes).
- What is the history of the Arctic-Pacific Ocean connection? Was there any deep-water communication during the Paleogene; Mesozoic? (requires Bering Sea drilling).
- What is the history of the Arctic-North Atlantic connection through the Labrador Sea? (requires drilling in the Labrador Sea).
- When was deep-water circulation terminated through the central American Seaway? Paleogene? Mesozoic? (requires drilling in the Caribbean).
- What were the paleoceanographic responses to the early middle Cenozoic construction of the Indonesian Seaway? (requires drilling on the northwest Australian margin and in the Caroline Basin).

Surface Circulation. The reconstruction of the positions of past surface water masses and modes of oceanic surface circulation through the study of the distribution of planktonic fossils in the sediment is a well-known technique. However, it is obvious that this is an impossible exercise without a reasonable geographical coverage; the question of what constitutes a reasonable coverage is an important one. McIntyre (1967) showed that the former position of the Gulf Stream and the main features of the distribution of the surface temperatures during the last glacial episode could be described using only a handful of cores (Fig. 8a). Although he and co-workers have subsequently used over 100 cores to better understand the late Pleistocene history of circulation of the North Atlantic Ocean (Fig. 8b), McIntyre's early study suggests that we would obtain a very valuable history of paleoceanographic change through the past million years with the aid of only a few carefully positioned hydraulic piston corer (HPC) sites; these would also teach us a great deal about circulation in the previous tens of million years, although wider geographical coverage would be needed to realistically reconstruct the oceanic circulation in the most distant past as it departed more and more from the range of the pattern of circulation documented for the Pleistocene. In the late Pleistocene, the Polar Front has occupied tracks ranging from its present position at one extreme to a more-or-less east-west line at about 40°N at the glacial extreme; to follow its positions back into the Neogene it will be necessary to obtain good records from the Norwegian Sea. This illustrates the

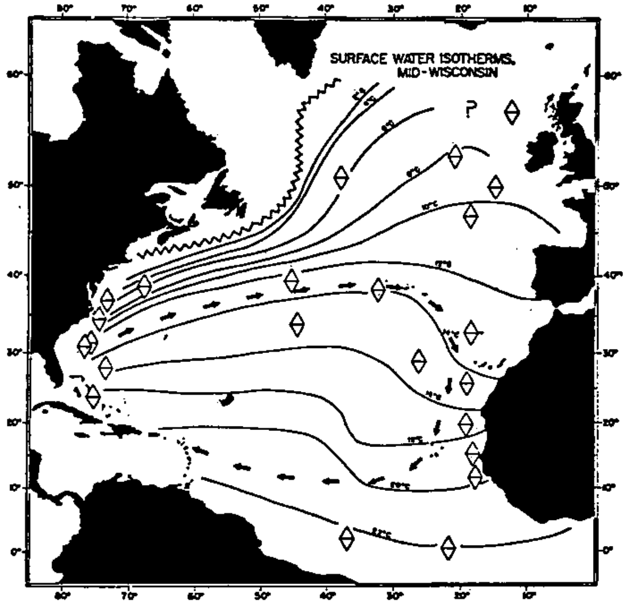


Figure 8a. The glacial surface water isotherms reconstructed by McIntyre (1967) using only a small number of piston cores (diamonds).

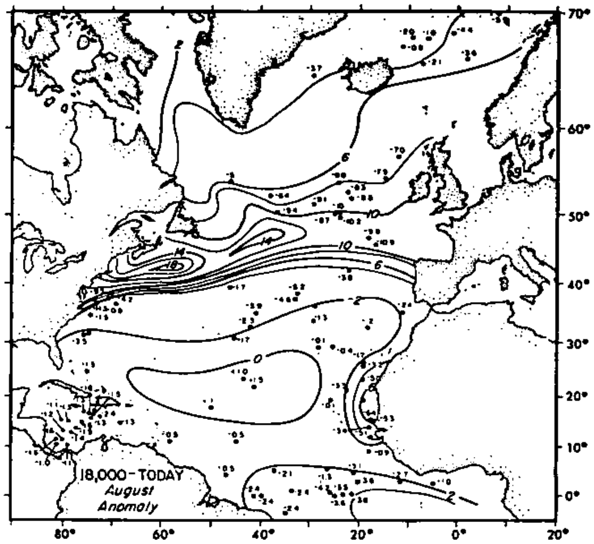


Figure 8b. The glacial temperature anomaly (degrees Celsius colder than today) reconstructed by McIntyre et al. (1976) using 100 cores. Examination of this figure suggests that a carefully selected small number of cores would provide an immensely exciting record of the history of oceanographic changes in the North Atlantic over at least the past million years, and probably much longer.

importance of planning sites in the light of growing knowledge. The reconstruction of past patterns of oceanic circulation is likely to continue to be a topic of active interest for at least the next decade as we gain an increasingly sophisticated appreciation of the interactions between climatic change and oceanic circulation during the evolution of Neogene climate.

In the more distant geological past, even quite small amounts of data can give an indication of past oceanic circulation; for example, Shackleton and Boersma (1981) have reconstructed mid-Eocene surface temperature with only about a dozen points on the globe, using oxygen isotope data (Fig. 9). However, they were severely limited by the core sites available, and it will be impossible to achieve a realistic understanding of the remarkably warm conditions which prevailed at that time without many more samples. It should also be noted that the oxygen-isotope method can only be used in well-preserved carbonate sediments. If faunal and floral distributions are to be used to reconstruct surface currents then a much more dense coverage is necessary before distributional patterns emerge. Ideally a grid of sites covering the whole ocean might provide us with coverage sufficient to map past patterns of circulation. However, practical constraints of time, funding, and the preservational patterns of deep-sea sediments make such a "grid" approach unreasonable. Rather, drilling efforts should be focused on transects of sites which cross frontal regions separating different water masses, boundary current regions with their large horizontal gradients in oceanographic character, and regions of zonal flow which are often associated with divergences and convergences. These very dynamic zones are the most sensitive to oceanographic change, and transects of sites which map their position and the steepness of their horizontal gradients through time are the most efficient means of providing history of near-surface circulation.

Oceanic Response to Transient Events. The major research problems proposed here are keyed to oceanic changes over relatively long periods of time (in excess of 23,000 yr). Some phenomena may not fit into these categories. For example the existence of isolated or partly isolated basins containing high-salinity water (the Mediterranean in the late Miocene) or low-salinity water (the Arctic in the latest Cretaceous) has been proposed. As these basins became connected to the interactive world ocean, they may have induced in the record of the surface ocean or deep ocean brief, spike-like events that lasted for short intervals (<10,000 yr) and may then have been succeeded by entirely different quasi-stable regimes. We envisage an effort to detect these "induction spikes" that mark short-lived transitions between regimes. Exceedingly high-quality records sampled at very close intervals are required to detect these events.

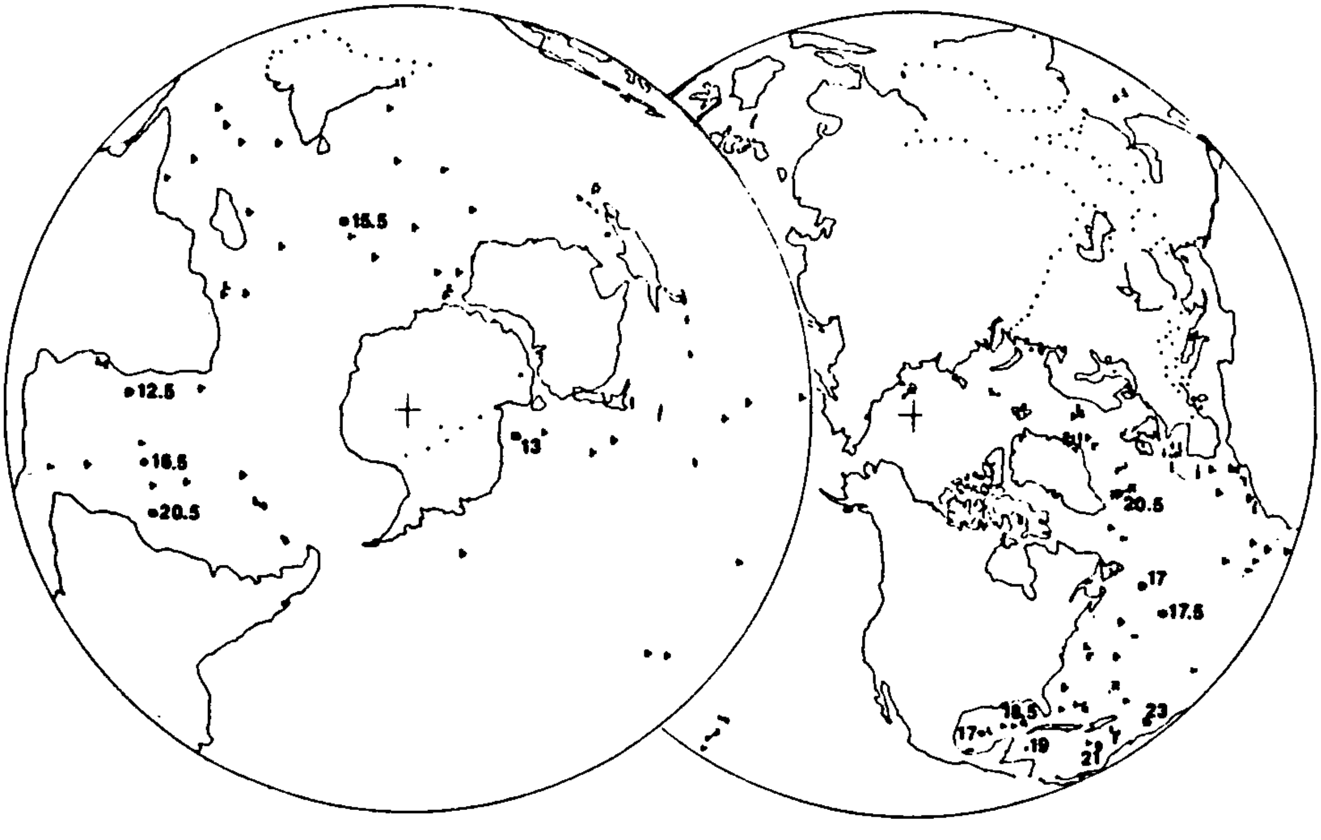


Figure 9. Eocene Ocean surface temperatures obtained by Shackleton and Boersma (1981) using the oxygen-isotope method. Even with such a small amount of data, this shows the scale of the latitudinal temperature gradient and the east-west gradient across the South Atlantic and poses interesting problems in paleoceanography.

B.3 Polar Oceans

One of the major gaps in understanding the oceanic paleoenvironment is that of the high-latitude regions of the oceans. This is true for the Neogene, Paleogene, and Mesozoic oceans. Thus, although many of the objectives listed above deal with high-latitude regions, we restate them here to emphasize their importance in a post-1983 drilling program.

It is widely appreciated that at present the circum-Antarctic flow is an important aspect of the global oceanic circulation. It is impossible to make a reasonable study of the history of this pattern of circulation for lack of suitably positioned DSDP sites. Moreover, the present work is rendered questionable by the fact that so much is based on piston cores containing large hiatuses; there is a shortage of continuous stratigraphic records against which to calibrate the information that has been obtained.

The development of the modern cold and highly productive south polar ocean from the rather warm times of the Mesozoic and early Cenozoic appears to have been an incremental and long-term process. Its Cenozoic history began with the opening of the Australian-Antarctic passage in Eocene times and proceeded to the opening of the Drake Passage in late Oligocene time, to the thermal isolation of the Antarctic continent and development of a large continental ice sheet by the mid-Miocene, to the development of the zone of extremely high productivity near the polar front in the late Miocene. This incomplete history is based primarily on plate reconstructions in the region and a very inadequate sample record. We know that large changes in thermal regime, circulation, and productivity did occur, but their exact timing, the patterns of change, and the mechanisms of change are still obscure.

The oxygen-isotope studies of DSDP Leg 29 drilled in high southern latitudes were of great importance for our understanding of the Cenozoic oceans; however, the apparent value of the "deep water" oxygen-isotope record of DSDP Site 277 from that leg is severely limited by the fact that the paleodepth was only of the order of 1000 meters; without a deeper, high-latitude site one cannot distinguish depth gradients from latitudinal gradients in the deep water. At present there is a significant latitudinal gradient in the temperature of the deep water near Antarctica as a result of the sinking of cold water formed on the continental shelf, and it is important to be able to measure past vertical and latitudinal gradients to determine the history of this formation of deep water. A vertical transect of sites as far south as possible would be the best way to tackle this problem.

The history of Antarctic Bottom Water is an important aspect of paleoceanography. At present this water mass forms by a freezing-out mechanism in the Weddell Sea. Without this mechanism, the sea water around Antarctica is not dense enough to form a bottom water because of the low surface salinity resulting from the high precipitation. It has been strongly argued that in earlier times there was no high-latitude bottom water, and that bottom water formed at low latitudes from highly saline shelves (Peterson et al., 1981). This hypothesis predicts the existence of very much smaller vertical gradients in the deep sea and essentially no latitudinal gradient in deep water near Antarctica, features that are easily testable isotopically with suitable drilling.

Some of the major changes seen in the Southern Ocean may be tied to oceanographic changes in the Northern Hemisphere and the injection of North Atlantic Deep Water into high southern latitudes. In the Northern Hemisphere, the geological history of the Arctic Ocean is a major gap in our knowledge. For the near future we will have to make do with inferences from the closest technically feasible sites in the Bering Sea and the northern Norwegian Sea, which become very important by default. In the more distant future it is essential that we obtain more information from the Arctic itself.

In conclusion, many of the major changes and events in Neogene global climate and oceanographic evolution largely reflect changes in high rather than middle or low latitudes. Important outstanding questions which require drilling at high latitudes for answers:

- What is the history of polar glaciation during the past 100 m.y.?
- Were there any significant icecaps or significant ice buildups in Antarctica in the Cretaceous? The early Paleogene? When did the existing icecaps become established?
- What is the history of Antarctic Bottom Water during the Cretaceous? Paleogene? Neogene? When did the Weddell and Ross seas become sites of formation of bottom water?
- What paleoenvironmental changes occurred in polar regions at the time of major threshold events at the Cretaceous-Tertiary boundary, Eocene-Oligocene transition, middle Miocene?
- What is the biogeography and evolution of marine plankton and benthos (foraminifera, ostracods) in higher latitudes during the Mesozoic; Cenozoic?

The most important sources of bottom water in the present oceans are in polar regions, especially Antarctica and the North Atlantic. Since the production of these bottom waters is directly related to glacial evolution and sea-ice production, an understanding of the climatic evolution in these areas is fundamental. Obtaining detailed stable isotopic records for the Mesozoic and Cenozoic in polar regions which can be compared to those of middle and low latitudes is a high priority.

Particularly crucial areas for both shallow coring and deep drilling include:

- The Kerguelen Plateau — vertical gradients away from the continent, history of the polar front, history of productivity.
- Maud Rise — vertical gradients near the continental margin.
- Sections of the Antarctic continental margin off the Weddell Sea — vertical gradients at the continental margin, history of bottom water production, history of productivity, vegetational history of Antarctica.
- Bering Sea — development of North polar sea in Pacific.
- Labrador Sea — development of North polar sea in Atlantic, development of glaciers.
- Norwegian Basin, Voring Plateau — develop-

ment of Arctic Seaway, history of Gulf Stream injection.

C. ORBITAL RESPONSE OF THE CLIMATE AND OCEAN

The study of past climate is one of the fast-growing areas of science; it is an area of international interest, a situation that is reflected in the existence of several international projects and committees devoted to it.

For timescales of decades to a few centuries, the prime source of information is man's observational records, supplemented by proxy data from such areas as the study of tree growth-rings. For longer timescales, the information contained in deep-sea sediments becomes more and more important. Although geologists have studied the ice ages for a century, the last decade of study of deep-sea sediments has revolutionized our understanding of the climatic changes involved and of their causes; we have a better understanding of the causes of climatic change in the timescale accessible to study in piston-cores of deep-sea sediment than on any other shorter or longer timescale. One reason for this is that one can obtain global coverage by sampling deep-sea sediments, and another is that one can obtain continuous records through past time. It must be appreciated that drilling does not in itself answer questions related to the causes of climatic change; it is very seldom that any conclusion relating to climatic change can be reached by the shipboard scientists. It is also the case that some of the material already recovered by drilling is capable of revealing information relating to climatic change, but much of it is either badly disturbed by the rotary drilling operation or has not been appropriately studied; thus in a program of finite duration one has to consider which problems are of importance now, and how they can be solved. In the following paragraphs a few important problems are outlined, together with proposals for their solution.

C.1 Response of World Climate to Orbital Variations

This question has been posed first, because it is a question that has been partially answered. We have an increasing understanding of the response to orbital variations over the past half a million years (Hays et al., 1976; Pisias and Moore, 1981), and our understanding is growing rapidly. This is one of the more successful aspects of the study of climatic change in the Quaternary. However, from the climatologist's point of view, the manner in which the climate responded over the past half a million years is hard to model quantitatively because of the hugely complicated effects of fluctuating ice sheets, with their well-known feedback effects. Indeed some scientists believe that the instabilities of the ice sheets themselves have been more important than the effect of orbital variations (see, for example, Ghil, 1981). Thus the response of the earth's climate to the same orbital forcing function, with boundary conditions which did not include major ice sheets over the northern hemisphere continents, is of intense interest.

Similarly, how do the oceans and the climatic system respond to orbital forcing when other major changes are made in the boundary conditions? For example, how is the spectrum of oceanographic variability changed by the opening of various gateways to surface and deep circulation? How do boundary changes in high latitudes affect the variability at low latitudes, and from this what can be deduced about the teleconnections within the oceans?

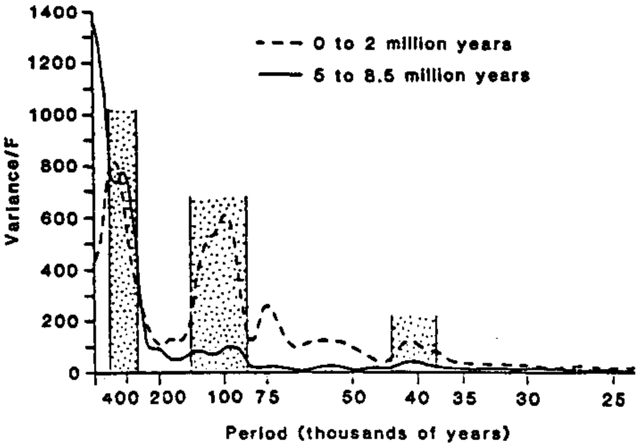


Figure 10. These variance spectra show how much stronger the effects of the 100,000-yr cycle were over the past 2 m.y. (dashed line) than 5 to 8 m.y.B.P. (solid line). The larger the peak, the more variability in the carbonate content of the sediment (and presumably in climate) is attributable to cycles having that period. The variability attributable to the 400,000-yr cycle remained the same, but that in the 100,000-yr cycle was about six times greater during the more recent period. Variability having periods between 40,000 and 100,000 yr also increased dramatically (Moore et al., 1982).

Orbital variation and insolation changes are not confined to the Pleistocene (Fig. 10) but have been potential causes of climatic change throughout earth's history. Records of such orbital periodicities are now known from the late Miocene (Moore et al., 1982; Prell and Gardner, 1982) and undoubtedly will be found in earlier records of oceanic response. The 100,000-yr cycle so dominant in most Pleistocene records appears to have been minor prior to the advent of large northern hemisphere ice sheets which formed about 3 m.y.B.P. (Shackleton and Opdyke, 1976; 1977; Moore et al., 1982). Its existence may depend upon amplifying effects due to ice, ocean, atmosphere interaction or on lithosphere, ice load interaction (Emiliani and Geiss, 1957). The late Miocene (5 to 8 m.y.B.P.) carbonate dissolution record at DSDP Site 158 contains a strong 400,000-yr cycle which may have resulted from the formation of the Antarctic ice sheet 13 to 14 m.y.B.P.

Recent studies of DSDP cores suggest that different parts of the Tertiary have experienced different amounts of climatic variation with varying frequencies as well as shifts in the modes of variability (Moore et al., 1982) (Fig. 10).

One major effort in the Cenozoic will thus involve a search of the climatic indicators for orbital (or other) cycles: Do they occur? In which ocean basins? At what frequency and strength? And with what phasing? "Phasing" may refer to the *relative* phasing of the several orbital periodicities or their phasing with respect to other climatic signals (eolian input, biogenic productivity) measured in the same suite of cores. Cross-correlation procedures can quantify these phase relationships, which are so instructive of cause-and-effect relationships. In this respect, the value of HPC cores as "multi-channel" recorders for paleoclimatic analysis is immense.

In order to address such questions concerning the effects of changing boundary conditions on the way the oceans respond to orbital forcing, three basic requirements must be met for each time interval studied:

1. The recovered sedimentary (proxy) records must have accumulated at reasonably high rates (a minimum of 2 cm/10^3 yr). This assures the resolution needed to define the main periodic components of the earth's orbits (Fig. 11).

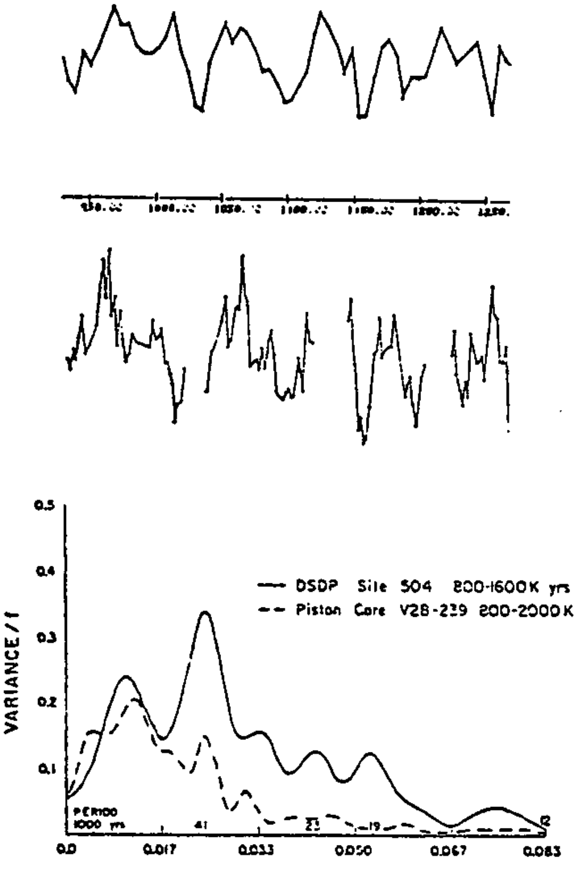


Figure 11. Top: A part of the oxygen-isotope record of DSDP Site 504 plotted as a function of estimated age (below), compared with a section of piston core V28-239 (above) covering the same estimated age interval from 0.95 to 1.25 m.y.B.P. Note the much greater amplitude of isotopic variation in the high-accumulation rate HPC site (4 cm/10^3 yr for DSDP Site 504, 1 cm/10^3 yr for V28-239). Note also between-core gaps in the DSDP Site 504 record. Bottom: A comparison of the estimated spectral density of the oxygen-isotope record of the lower Pleistocene sections of DSDP Site 504 and of V28-239 (N. Shackleton, pers. commun.). Spectral density in the bandwith 20,000- to 40,000-yr periods is much greater in the DSDP Site 504 record.

2. The recovered records must be relatively complete so that a detailed time series can be constructed (Fig. 12).
3. The records must be located so that they monitor all parts of the atmosphere/ocean/ice system at as many different locations as possible. The effects of the orbital parameters vary with latitude as may the response of different parts of the climatic system; thus a broad global coverage of detailed time series is needed.

The areas in which extensive sampling is required are the North and equatorial Pacific Ocean, the subantarctic Indian or Atlantic oceans, and the northern Indian Ocean. Each of these areas would warrant approximately ten sites, all sampled with double overlapped HPC coverage to provide a gap-free record. The areas are those which are known to contain appropriate sediments for climatic study; it is highly likely that as the science proceeds, further sampling would be required in the same areas. In addition there are other areas in which the required sampling is at present less predictable: for example, the northeast and northwest Pacific, the southwest Pacific, the Mediterranean Sea, the South Atlantic, the Norwegian Sea.

In addition to this array of high-resolution records, it will be necessary to gradually build up a global array of cores. The reason is that there are many areas (for example, the centers of the oceanic gyres) from which climatic information is very important but hard to obtain because of the low rates of accumulation. Because of the importance of carbonate sediments for many climatic studies, priority should be given to coring the shallowest points, even though the records from such points may be discontinuous and difficult to interpret.

C.2 Orbital Tuning

The relationship between orbital variations and climatic change provides an important opportunity to improve the chronology of deep-sea sediments (Hays et al., 1976). By recognizing orbital frequencies in the deep-sea record, chronological information can be obtained in two ways.

Ideally climatic cycles related to variations in tilt (obliquity) and precession can be recognized from the sea floor at a number of sites and counted back through time, carefully relating biostratigraphic and paleomagnetic data to specific cycles. These cycles in the sediments can then be correlated to a set of obliquity and precession curves, the ages of which have been determined by astronomical calculations. There have recently been developed precise statistical methods for making these correlations. This procedure of counting cycles from the present back through time is possible, but it rests on the recovery of complete records. The hydraulic piston corer (HPC) can certainly provide continuous records back farther in time than conventional piston cores, yet for older records gaps will certainly be present. Even in records that contain gaps there is time information available provided that the continuous record between gaps is long enough to measure frequencies similar to orbital frequencies. Since absolute time ini-

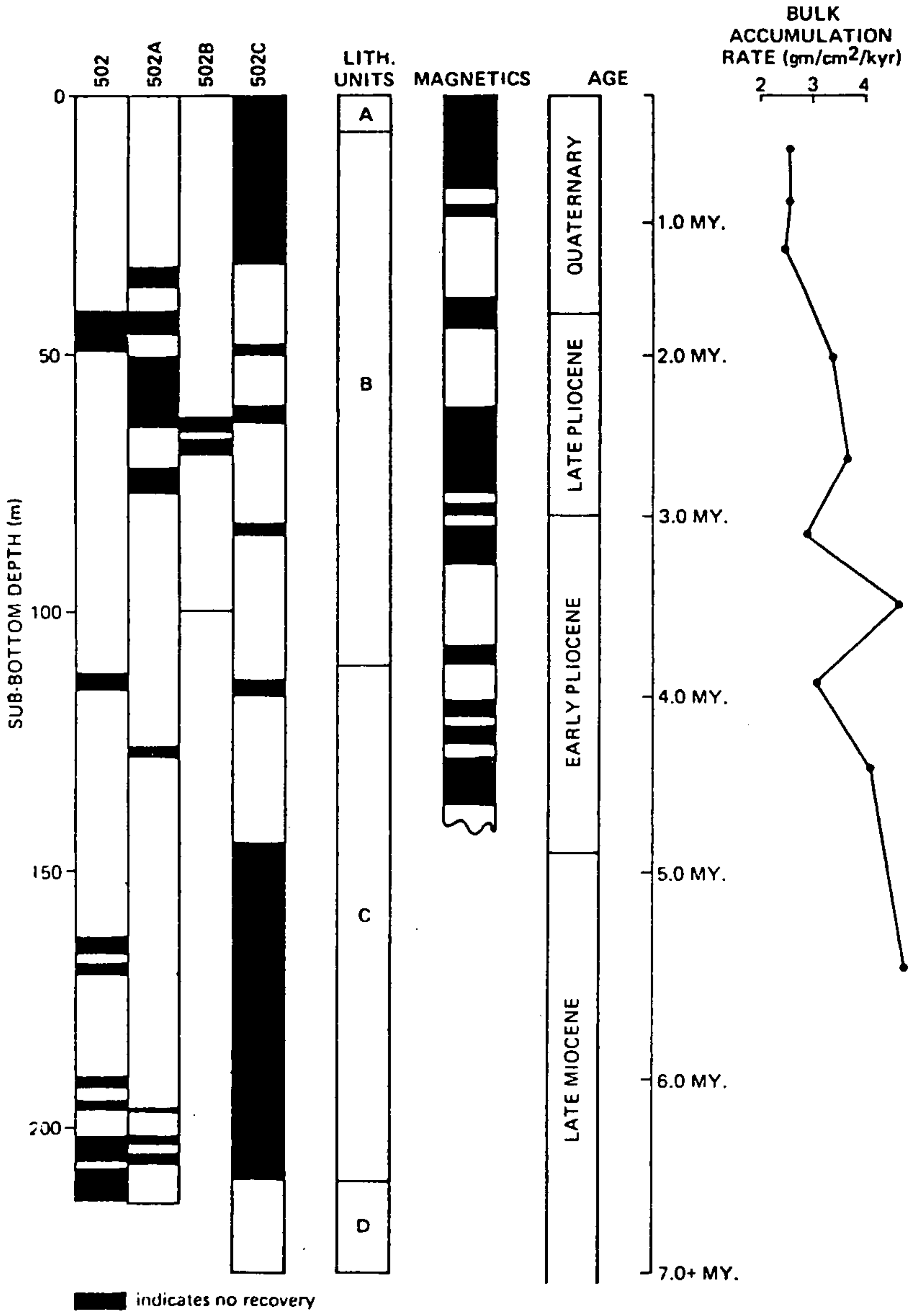


Figure 12. The manner in which complete recovery of DSDP Site 502 was sought by select redeployment of the HPC (Gardner and Prell, 1980). This diagram was constructed on the assumption that all recovery is useful, whereas in practice there is a disturbed section at the top of each 4.5-meter core. A longer core barrel may be expected to reduce the percentage of disturbed material so long as its penetration is not limited by the physical properties of the sediment.

tially will be known poorly, spectral analysis of these older records cannot be precise. However, even though time is known imprecisely, in many instances it will be possible to detemine the ratio between the frequencies present. If the ratios between specific frequencies in the sediments are the same as the ratio between orbital frequencies, then it is very likely that the sedimentary record is reflecting orbital forcing. The length of time represented by the section between the gaps that correspond to specific orbital frequencies can then be measured in the sediment. The potential for a very accurate time scale spanning the last several million years will provide the basis for a host of studies not possible with the present approximate chronology based on radiometric dating.

D. GEOCHEMICAL CYCLING

The inorganic geochemistry of marine sediments is important to the understanding of several important processes. Chemical analyses combined with stratigraphic information give rates of deposition for elements whose geochemical cycles are not well understood. More specific studies of trace elements may show important differences between sources of sediment including black shales (Thierstein et al., 1981).

Oxygen-isotope studies of paleotemperature have been an important guide in paleoenvironmental studies. The δC^{13} and δS^{34} record of marine carbonates and sulfates show large changes in the ratio of reduced to oxidized forms of carbon (organic C:$CaCO_3$) and sulphur (FeS_2:$CaSO_4$) buried in sediments during geologic time. The $^{87}Sr/^{86}Sr$ ratio in marine carbonates reflects the relative amounts of granitic and basaltic strontium entering the oceans. These isotope curves show a striking correlation with one another and with sea level. This suggests that there are long-term interactions between tectonics, climate, ocean circulation, and geochemical cycles. The processes relating these factors are not well understood. Detailed studies of the geochemistry and distribution of deep-sea sediments, in conjunction with tectonic and paleoenvironmental studies, are needed to unravel these cycles.

D.1 Oceanic Biogeochemistry

Significant advances have been made during recent years in understanding the factors that control the $CaCO_3$ and silica budgets of the oceans (Berger, 1970; Heath, 1974). Foremost among these "biogeochemical" factors is the biologic activity of shelled plankton, which sequester Si and $CaCO_3$ in their shells at rates far in excess of annual river delivery of these elements to the ocean. This biological overrun forces significant chemical dissolution and recycling of both components within the oceans to balance the budgets. The second critical component is oceanic circulation: vertical upwelling determines the amount and location of the accelerated biologic activity, while lateral deep circulation determines the nutrient and silica content of the upwelled waters and the corrosiveness of bottom waters to $CaCO_3$ and silica on the sea floor.

The Mesozoic record covers the time of the development of the major calcareous plankton groups (foraminifera, coccolithophorida) that at present not only provide the bulk of the fossils in marine sediments but also make the major contribution to the global cycling of elements in the ocean. How did the ocean function geochemically in the absence of this biogenic cycling? What interaction was there between changing ocean chemistry and plankton evolution? How did this affect atmospheric composition.

The Neogene tectonic changes in oceanic "gateways" must have significantly altered the shallow and deep oceanic fertility and, hence, the production and preservation of calcareous and siliceous microfossils. Studies of siliceous sediments in HPC cores provide an areal view of geographic fluctuations in the extent of the fertile belts of divergent upwelling, past and present; studies of $CaCO_3$ in HPC cores also reach into those lower-fertility regions which provide optimal depth control on past vertical fluctuations in the carbonate compensation depth or "carbonate snow line."

Oceanic biogeochemistry can vary significantly on time scales as long as millions of years (e.g., Van Andel et al., 1977) to as short as thousands of years (Berger, 1977). The greatest impact of high-resolution stratigraphy will probably be in opening a window to variations on the scale of the orbital cycles (23,000-100,000 yr). One study of conventional piston cores in the Pacific Ocean showed that Pleistocene dissolution of $CaCO_3$ has varied with significant 23,000-yr and 100,000-yr spectra, but that it has lagged some 6000 yr behind the signal of isotopic ice volume (Moore et al., 1977). This lag was ascribed to the slow response of the North Atlantic to deglacial warmings (thus delaying the renewed formation of deep water) and to slow response of the Ca^{+2} and $CO^{=}$ ion chemistry of deep waters in the world ocean.

Neogene biogeochemical studies will emphasize the frequency-response characteristics discussed previously; the data gathered and conclusions arrived at will provide a view both of near-surface processes (changes in productivity and near-surface preservation) and deep-ocean processes (changes in dissolution/preservation on the sea floor). These investigations of oceanic biogeochemistry, focused on regions of near surface vertical water influx and of lateral deep-water flow, thus compliment the studies of thermal response of the surface ocean.

D.2 Oceanic Anoxic Events and Organic Carbon Sinks in the Mesozoic Ocean

One intriguing problem of Cretaceous and Jurassic paleoceanography is the origin of widespread, carbonaceous-rich sediments in nearly all ocean basins and intracontinental seaways from about Barremian (ca. 121 m.y.B.P.) through Cenomanian-Turonian (94 m.y.B.P.) and, locally, later time. These deposits have been attributed to "Oceanic Anoxic Events" (OAE) (Schlanger and Jenkyns, 1976) (Fig. 13) and variously ascribed to expansion of the oceanic oxygen minimum layer and/or to stagnation of entire ocean basins.

Based on the stratigraphic distribution of organic,

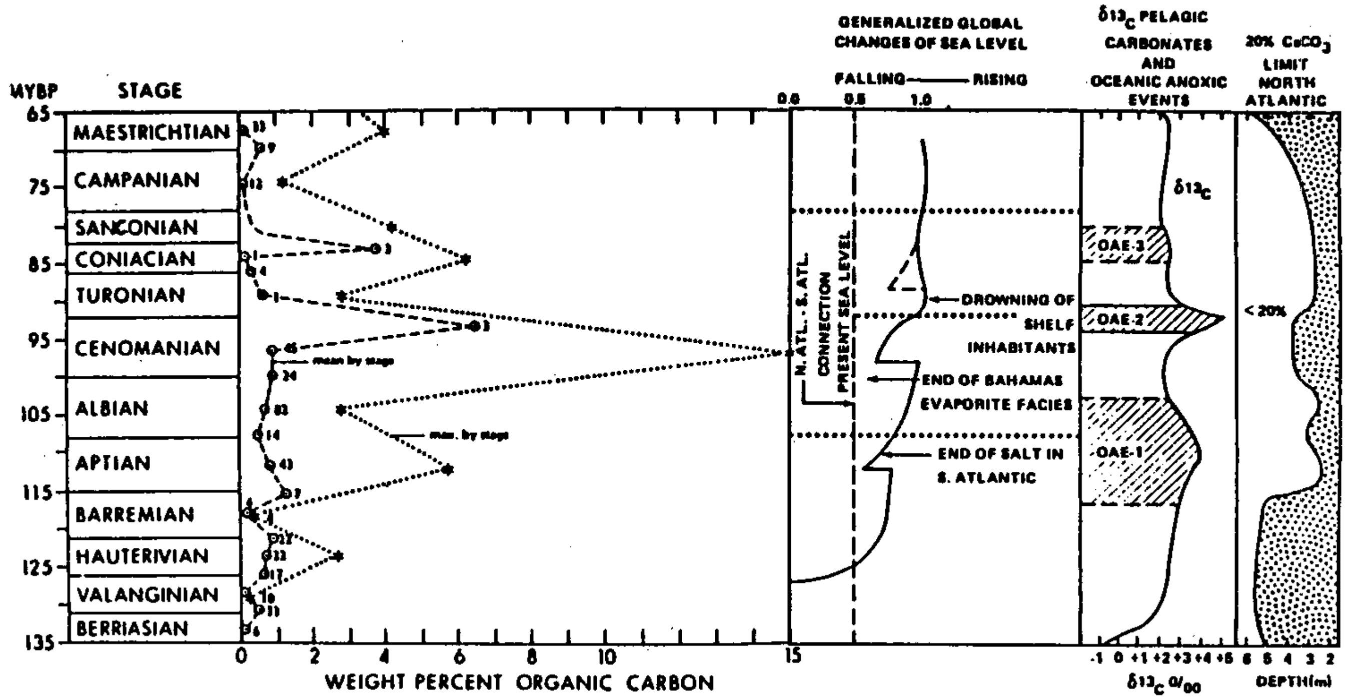


Figure 13. Weight percent organic carbon in Atlantic DSDP cores correlated with global changes of sea level, "Oceanic Anoxic Events," δC^{13} of pelagic limestones, and changes in the level of the calcium carbonate compensation depth. Compiled from Arthur and Schlanger (1979) and Scholle and Arthur (1980).

carbon-rich sediments in Cretaceous sections it has been proposed that certain time envelopes — Barremian to early Albian, late Cenomanian to early Turonian, and Coniacian to Santonian — were characterized by OAE's; i.e., periods of time when the world ocean tended towards anoxia. As shown in Figure 13 these periods correlate with transgressions. Scholle and Arthur (1980) have discovered that these periods are also marked by δC^{13} "spikes" (Fig. 13, col. 3). These spikes are thought to represent times of increased rates of organic carbon preservation in sediments. They have calculated that in the Cenomanian-Turonian OAE carbon was preserved at 3.1 times the present rate. This sequestering of organic carbon has important implications for prediction of hydrocarbon resources and geochemical cycles.

In order to (1) establish the linkage between present-day anoxic ocean waters and sediments deposited within and below such water and (2) deduce the degree of oxidation and organic carbon preservation in Mesozoic sediments, a two-phase drilling program is recommended:

1. Two contrasting models for environments, under which important volumes of organic-carbon-rich, anoxic sediments are deposited, are isolated euxinic basins (e.g., Black Sea) and the midwater, oxygen-minimum zone. It is, therefore, most important to understand the various Holocene and sub-Holocene environments in which anoxic sediments are formed, especially for extrapolation to and prediction of ancient occurrences of anoxic sediments, ocean chemistry, and the estimation of potential of sources of hydrocarbon for various regions and intervals of geologic time. Varved sediments permit an analysis of the annual record of oceanic conditions, surface productivity, etc. extending back hundreds of thousands to millions of years. Such records are also invaluable for understanding high-frequency oceanic responses.

We would like to examine the imprint of a midwater, open-ocean, oxygen-minimum zone on continental slope sediments. The types of problems to be investigated are: (1) the variation in population and diversity of benthic faunas, intensity of bioturbation and consequent preservation of a fine-scale (annual) record of variations in sediment and organic supply, and the record of variations in levels of oxygen in bottom water in response to climate change; (2) the amount and type of organic matter preserved in the sediments and the extent of early diagenesis (hydrocarbon potential); (3) chemistry of pore water and relation to authigenic mineral phases including, for example, the origin of authigenic dolomite and phosphorite accumulations and preservation of calcareous and siliceous organisms. These studies are important for economic considerations and for estimating oceanographic factors (e.g., levels of oxygen and productivity) in the sedimentary record. Drilling targets would include the Peru Shelf, southwestern African shelf, northern Indian Ocean-Persian Gulf, the California Borderland and the Nitinet and Astoria fans.

2. As shown in Figure 14 most of the organic-carbon-rich sediments drilled to date have been in the Atlantic basins. We recommend that drilling for the purpose of detecting and interpreting Mesozoic anoxic events be concentrated in the area of the Pacific Basin bordered by the M-1 and anomaly 32 magnetic lineations. This Pacific program would define superocean paleoenvironments. Many of the sequences of black shales exhibit alternations in lithology that

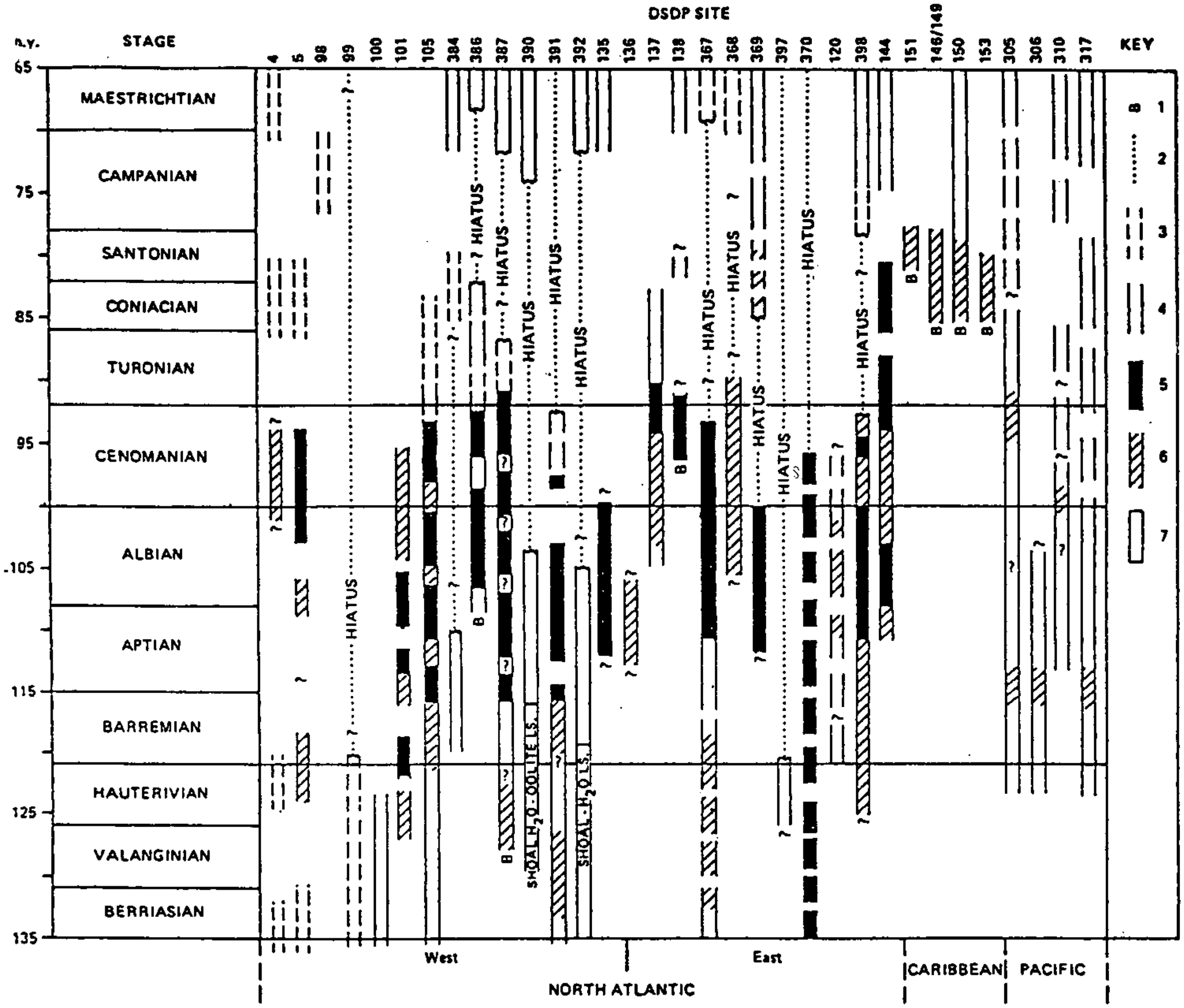


Figure 14. Summary of ages of Cretaceous black shale or other organic-rich facies in North Atlantic, Caribbean, and selected Pacific DSDP drill sites. Note concentration within the Hauterivian through Cenomanian interval. Symbols: (1) Site reached basement. (2) Hiatus. (3) Age uncertain or inferred. (4) Cored interval with age documented. (5) Primarily dark-colored, relatively organic-rich sediment showing evidence of anoxic or very low oxygen conditions. (6) Primarily dark-colored organic-rich sediment showing evidence of low oxygen to oxygenated conditions. (7) Sediment evidencing well-oxygenated conditions. (Arthur, 1979).

characterize sediments at this time. Is the apparent cyclicity of the shale sequences related to climatic forcing (possibly astronomically controlled) or is it the result of a complex feedback loop? Did the carbon input vary cyclically, or was the primary control the rate of formation of deepwater? Such questions require a good time control and carefully planned site distribution.

D.3 The Marine Record of Continental Environments

In the modern oceans proximity to land masses strongly influences marine sedimentation. Terrigenous clays, silt, sand, and various organic materials often constitute a large part of the total sediment. Similar conditions occurred in past geological times, especially when continental pedogenesis was more active than at present (Mesozoic to Paleogene climate), the oceans narrower (Atlantic, Indian Ocean), and subaerial vulcanism more active (e.g., Paleogene of the northwest Pacific and South Atlantic). Terrigenous materials, particularly clay minerals, are often unaltered or only slightly affected by diagenesis where sedimentation rates are moderately high. Thus the terrigenous components of marine sediments reflect land paleoenvironments and their interdependence with the marine environment (Fig. 15). In areas where diagenetic effects occurred due to sea water, volcanic, or hydrothermal activity, these components are very important in distinguishing the respective

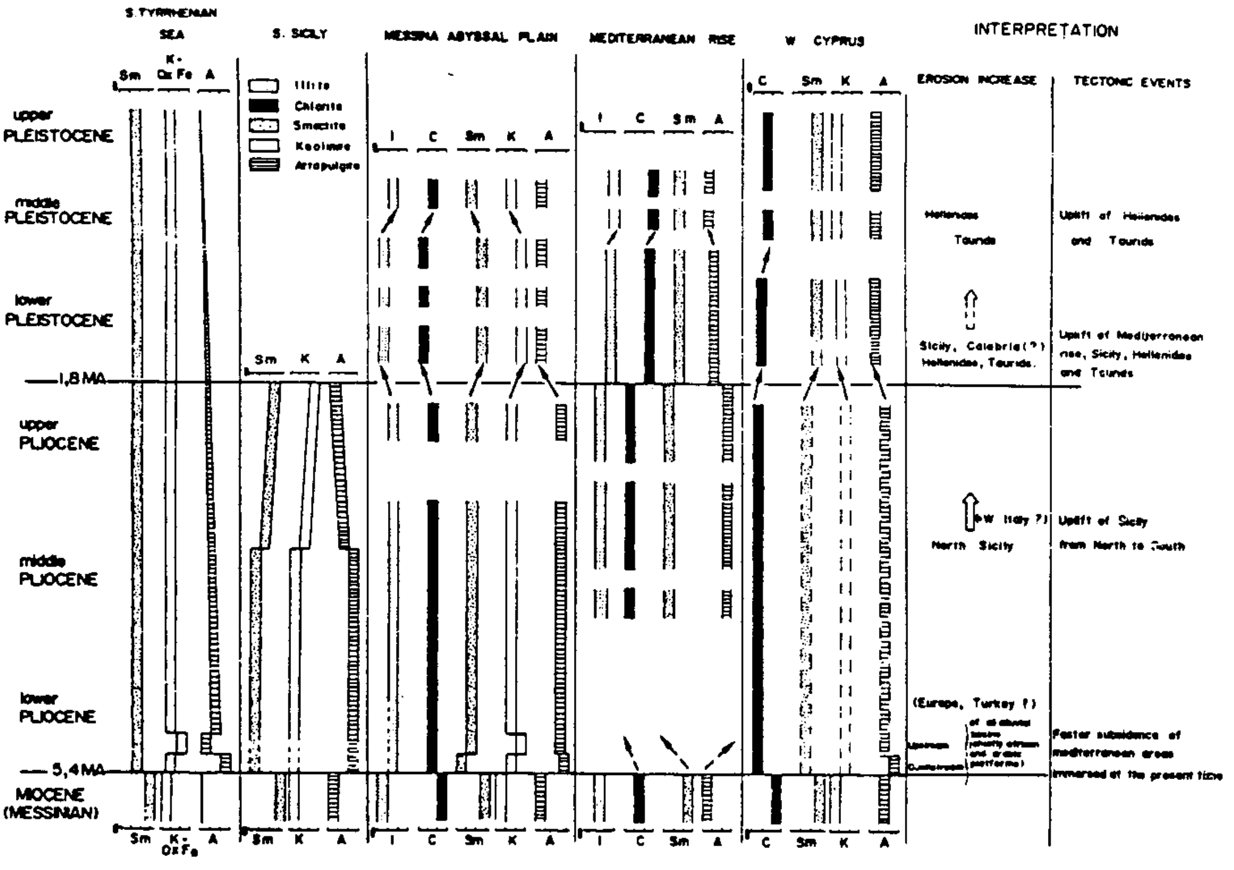


Figure 15. Plio-Pleistocene tectonic evolution of the Mediterranean area, from clay sedimentary succession.

importance of continental and oceanic influences.

The information in the pollen and spore record of deep-sea sediments is readily interpretable as indicating the humidity, temperature, and wind regimes of nearby continental regions and is also useful in interpreting the sources of sedimentary organic matter (Habib, 1979). Similarly, wind-blown dust, especially quartz, can be used to indicate both arid environments of the past and patterns of the atmospheric circulation which transported the dust (Leinen and Heath, 1981; Rea and Janecek, 1981; Prospero, 1981). Clay mineralogy and the geographic distribution of clay minerals have been used as indicators of both climate and oceanic circulation for many years (cf. Biscaye, 1965). Similary interpretations of changes in clay mineralogy downhole, rather than geographically, by such workers as Chamley (1979) promise to be extremely informative in paleoenvironmental reconstruction.

For these reasons it should be an essential goal of any future drilling program to conduct interconnected mineralogical, geochemical, palynological, and microlithological studies on those areas of the ocean subjected in the past to terrigenous influences. The result of such combined investigations will be specific information concerning climate and pedogenesis, erosion, terrestrial geomorphology, rates of mechanical and chemical erosion, transgression/regression sequences, tectonic activity or stability, subaerial and submarine vulcanism, eolian and seawater transport of fine-grained material, effects of gateways, and indications of the sources and motions of major deep-water masses.

E. BIOTIC EVOLUTION AND BIOGEOGRAPHY

Paleontologists study evolution by relating observations of change extracted from the fossil record to the patterns of change predicted by the mechanisms of evolution. But both the patterns of change and their underlying causal mechanisms exist on different levels and no one approach or type of data can provide a complete understanding of evolution.

At least three major levels of evolution can presently be recognized: microevolution, or changes within populations of individual species, speciation, and the evolution of entire biotas and major bauplans.

Micropaleontologic data has an important role to play in the study of evolution over the next few decades. Because of the unusually complete preservation of diversity, the availability of accurate, high-resolution chronologies, and because of the ease by which large, globally distributed samples can be obtained, microfossil records from the deep ocean offer an important means for the study of evolution of species-level phenomena, and the evolution of biotas.

E.1 Speciation and the Tempo and Mode of Evolution of Species

In 1972, Eldredge and Gould examined from a paleontologic viewpoint what was then the most popular model of speciation — the peripheral isolate model of Mayr. Their predictions of punctuation and stasis created considerable enthusiasm among paleontologists, since in testing these predictions paleontology is able to contribute significantly to answering one of the central questions of evolutionary biology — the origin and evolution of species. Despite innumerable studies, little progress has been made in testing for the presence and frequency of punctuation or gradualism. This is primarily the result of the inadequate terrestrial and macro-invertebrate fossil record in these studies. Preservation is locally spotty, often completely absent over larger areas, and stratigraphic control generally is very poor. In the decade since Eldredge and Gould's classic paper, theoretical developments have occurred as well. Evolutionary theorists have become increasingly aware of the importance of geographic variation and reproductive strategy to the choice of an appropriate model of speciation. Secondly, the concept of hierarchical evolutionary mechanisms has led to the recognition of the importance of studying phenomena between species versus within species — regardless of the tempo of change (punctuated or gradual) within lineages (Eldredge and Cracraft, 1980).

To answer these questions about phenomena within and between species in evolutionary paleontology it is necessary to obtain fossil records which span long periods of time and that are undisturbed by the effects of dissolution, diagenesis, and inadequate sampling (Fig. 16). A global set of samples is needed to ensure that the complete range of geographic variation known to exist in many — if not most — biological groups (Endler, 1977) is available for analysis. Accurate methods of correlation must exist to tie together individual sites into a comprehensive geographic and temporal framework.

HPC cores of the deep oceanic record offer several major advantages for evolutionary studies. Coverage of much of the world ocean is possible, including the isolated basins or water masses in which evolution could occur prior to introduction of newly evolved species to the rest of the world ocean. Paleomagnetic and isotopic stratigraphies offer the means of achieving accurate and detailed correlations between regions. Uncertainties of methods of dating for the youngest Neogene are in the range of a few thousand to a few tens of thousands of years. With the relatively linear sedimentation rates typical of many deep-sea cores, it will be possible to measure evolution from a global viewpoint at time steps of thousands of years, an improvement of two to three orders of magnitude over most previous studies.

Because of the nearly complete preservation of original taxonomic diversity, and because of the very large sample sizes which can routinely be obtained, it is possible to study not just a single fortuitously preserved lineage, but entire phylogenetic classes. This permits paleontology for the first time to directly examine evolutionary patterns both between and within species, speciation and extinction, and to see how each is related to patterns of geographic variation.

Taken together, these advantages make the record of deep-sea fossils the best available source of direct data on many aspects of evolutionary change at the

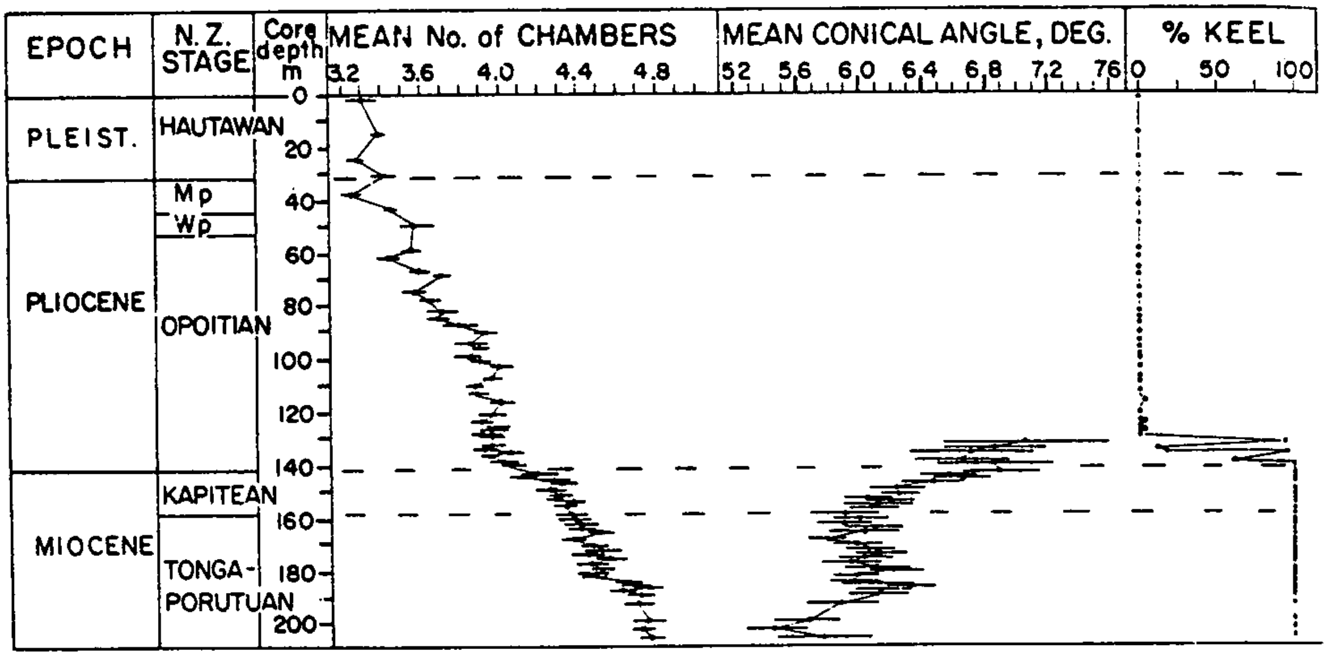


Figure 16. Variations in the mean number of chambers in the final whorl, the mean conical angle, and the percentage of keeled specimens in members of the *G. conoidea-G. inflata* lineage observed by Malmgren and Kennett (1981) in DSDP Site 284. There is no possibility of paleomagnetic control in this rotary-drilled site, and it would be impossible to exploit the full potential resolution of this site due to drilling disturbance. However, this foraminiferal group would clearly repay further study, for which the immediate requirement is a suite of sites at about 5° latitudinal intervals in the southwest Pacific, with palaeomagnetic control.

level of species. We propose that in the post-1983 program of ocean drilling a major effort be directed to testing the two models of speciation (punctuated equilibrium versus gradualism).

E.2 Macroevolution: Evolutionary Radiations, Mass Extinctions, and Biogeographic Realms

The evolution of the oceanic biota and the histories of their biogeographies are recorded in the sediment beneath the sea. As a result of deep-sea drilling, much has been learned from this record about evolution and the development of biogeographic patterns in the planktonic realm, especially in Cenozoic radiolaria, foraminifera, diatoms, and calcareous nannofossils (Haq et al., 1977; Haq, 1980; Kennett, 1981; Bukry, 1981 and others). Several episodes of extinction and re-radiation characterize the record of the last 100 M.Y. The taxonomic base upon which the study of biotic evolution rests is a relatively complete and accurate representation of actual biotic diversity, particularly in the foraminifera. The troubling incompleteness of diversity data from the shelly invertebrate shelf biota (Sheehan, 1977) is much less apparent in at least some marine microfossil groups.

Much less is known about the taxonomy, evolution, and biogeography of Mesozoic plankton and even less about deep-sea benthos. The available data suggest that both the evolution and biogeography of marine biota are intimately linked to the changes in oceanic environment, but evolutionary turnovers in the benthos and plankton show different patterns of change (Douglas and Woodruff, 1981). Major events of radiation or extinction in planktic foraminifera, for example, are generally not in phase with benthic foraminifera in the Mesozoic but are in phase in the Cenozoic. In the Cenozoic, evolutionary and biogeographic changes in the marine biota tend to parallel climatic fluctuation.

Much remains to be learned about the mode and tempo of macroevolutionary change, the relationships between evolution, biogeography and climate, and the mechanisms in the oceanic environment which cause evolutionary changes and mass extinction.

E.3 External Causes of Evolution and Extinction in Biotas

Two factors have been extensively discussed as the cause of massive evolutionary change: changes in climate and catastrophic physical events (such as extraterrestrial impacts).

Evolutionary changes in marine plankton and deep-sea benthic foraminifera appear directly linked to changes in the oceanic environment. Major radiation and extinction events roughly coincide with the step-like transitions in oceanic and climatic state such as in the Eocene-Oligocene and mid Miocene. The record for planktic foraminifera shown in Figure 17 gives an idea of the variation in taxonomic diversity in one group compared to the changes in the thermal structure of the tropical ocean. With improved core quality and high-resolution stratigraphies, it will be possible to examine evolutionary rates as a function of several climatic variables at different latitudes and in different ocean basins.

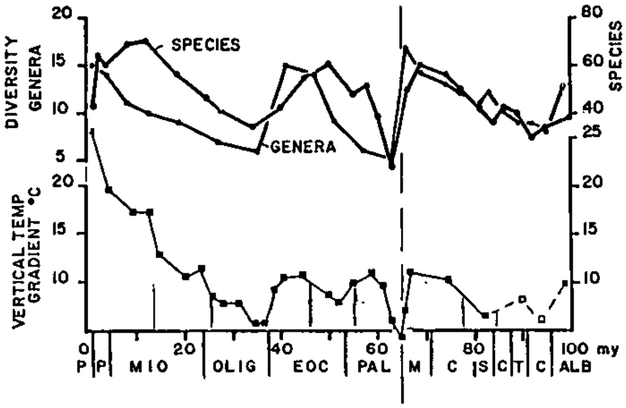


Figure 17. Comparison of the trends in planktic foraminiferal diversity and the vertical thermal gradient. Diversity data compiled from various sources. The vertical thermal gradient (difference between temperatures of surface and bottom water) for low latitudes is based on Pacific foraminiferal, oxygen-isotope, and paleotemperature (Douglas and Savin, 1979; unpublished) data which assume ice-free poles prior to the Eocene.

HPC sites in high latitudes will produce major improvements in stratigraphic resolution. This will permit a detailed analysis of the development of endemic diatom and radiolarian biotas during the Cenozoic that are intimately linked to changes in high-latitude circulation.

Recently proposed ideas to explain the biotic extinctions at the end of the Cretaceous emphasize the catastrophic and instantaneous (geologically) nature of the event. To test these ideas will require the recovery of continuous and undisturbed boundary sequences in different oceans, depths, and latitudes. The Cretaceous-Tertiary transition has been cored at several sites in the deep ocean (e.g., DSDP Sites 10, 47, 767, 310, 356, 384, and 524), but only two (Sites 356 and 384, and possibly 524) appear to be stratigraphically complete and without serious drilling disturbances. At DSDP Sites 356 and 524, the sequence has been expanded by the down-depth transport of sediments. Efforts should be made to locate possible sites that can be recovered by HPC, such as on the Shatsky Rise in the western Pacific.

F. PAST BEHAVIOR OF THE EARTH'S MAGNETIC FIELD

F.1 Magnetostratigraphic Record

The stratigraphic record of direction, intensity, and other characteristics of sediment magnetization is, of course, not only an invaluable tool for stratigraphic correlation; it is the prime data for any magnetic study. Thus whether magnetic measurements are made as a service to the overall stratigraphic effort or in order to study a particular aspect of the earth's magnetic or tectonic history, the first requirement must be that the sediment is recovered without loss of information.

The advent of the HPC has been a great step forward, because it is now possible to recover relatively undisturbed sections of unconsolidated sediments that, when recovered by rotary drilling, are so distorted as to be all but useless for magnetic studies. However, there are certain technical requirements of which the most important is *azimuthal orientation of recovered section*. In equatorial sediments it is not even possible to discriminate normal and reversed polarization as it is in higher-latitude deposits. Lack of azimuthal orientation seriously compromises the utility of paleomagnetic data for many of the studies outlined below.

F.2 The Record of Polarity Transitions

It is well known that the direction of the Earth's magnetic field has reversed several times per million years over the past 80 m.y. The record of behavior of the field during these polarity transitions will provide important data for understanding the origin of the Earth's field, but in piston cores only the most recent transitions are accessible for study in sufficient detail and then only in a few areas of the ocean. On the basis of study of one boundary of the Jaramillo Event Opdyke et al. (1973) have estimated that the duration of the reversal was about 5000 yr (Fig. 18). Valet and Laj (1981) made a similar estimate on the basis of a careful study of two reversals in a land section in Crete. The difficulty of using land sections is highlighted by the fact that they were unable to identify which of several known reversals were under study. It is over the 5000 yr of transition that we are interested in charting events. According to one model (Hoffman, 1977; Fuller et al., 1979) a different record would be observed in each hemisphere, depending on the dominance of quadrupole or octupole field components; we estimate that an adequate test of this model will require:

A minimum of eight sites, widely spread in both hemispheres.

Each site cored twice or three times. It is absolutely essential to distinguish features that represent the history of the magnetic field from artifacts of sedimentation or drilling disturbance.

The same geographical coverage for a good number of reversals. About 20 reversals are accessible from the past 5 m.y. We recommend that sites be planned to concentrate on these reversals since there is evidence that, in general, sediments deposited in this interval preserve a better magnetic record and are, therefore, more suited to this study than late Miocene sediments (this may in part be a result of greater wind transport of terrigenous material into the oceans during the late Neogene).

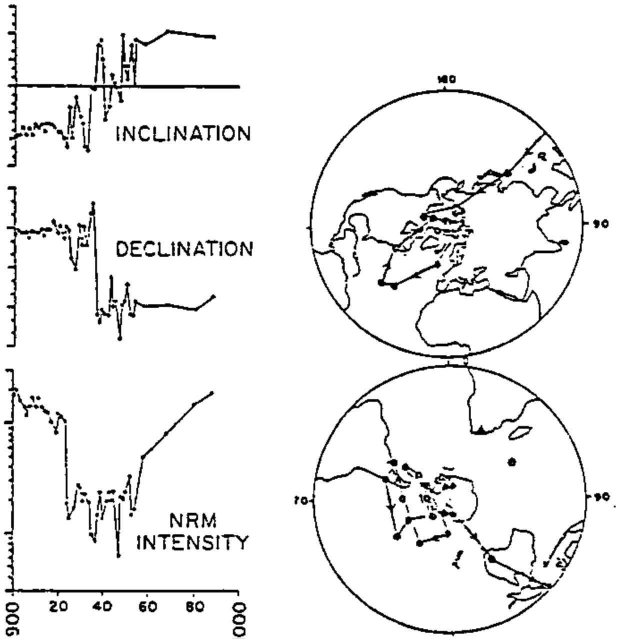


Figure 18. Paleomagnetic record (inclination, declination, and intensity) of the older polarity transition of the Jaramillo subchron, as measured in deep-sea sediment core RC14-14 (Opdyke et al., 1973). The path of the virtual geomagnetic pole corresponding to this transition is shown on the right. It would be impossible to obtain geographical coverage of this event using conventional piston cores; indeed it has not even been possible to obtain a core to duplicate this record in the 8 yr since it was first published.

F.3 Excursions of the Magnetic Field

There have been many reports, a good proportion of them poorly substantiated, of occasions during which the Earth's magnetic field has either reversed very briefly or else undergone some part of the reversal pattern but emerged in the same orientation. The precise nature of at least the most recent of these events will emerge from the study of conventional piston cores and from the study of modern and ancient lake sediments. However, the distribution of these events in time is again of great importance for theories of the origin of the Earth's magnetic field.

Harrison (1969), Cox (1975), and Phillips (1977), among others, have made statistical calculations predicting the frequency of occurrence of reversals. Unfortunately, the testing of these analyses is hampered by a deficiency of the available record which lacks the resolution to record the true frequency of polarity intervals shorter than about 10^4 yr. Consequently the various statistical models can only be tested fully by analyzing long records with a resolution approaching 10^3 yr. Thus the first requirement is a site where the rate of sediment accumulation approaches 10 cm/10^3 yr.

Data from volcanic lava flows on Iceland have suggested that there may be additional reversals over the past 20 m.y. which are not always apparent on the reversal time scale derived from marine magnetic anomalies (Watkins and Walker, 1977; Watkins et al., 1977; Harrison, 1980; Saemundsson et al., 1980). Data from the deep-sea sediments could be used to check these short events in order to see if they are recorded in other parts of the world or if they represent only local field behavior.

One model for explaining the apparently geographic localization of some of these excursions (Harrison and Ramirez, 1975) relates them to point sources on the core-mantle interface which only affect a limited area at a given geological instant. Thus it is essential that the same time interval be studied in several geographic locations. Because one aspect of this theory is that a particular magnetic excursion may move geographically, it is important that a high-resolution tool be available for correlating records in different areas independently of the magnetic record. Thus ideal sites would be in areas in which very high-resolution oxygen-isotope stratigraphy will be available.

This study will be of considerable importance for a second reason; that is, a means of investigating the meaning of the so-called "tiny wiggles" (Cande and LaBrecque, 1974) which are observed in a detailed analysis of patterns of marine magnetic anomalies. These short-wavelength magnetic anomalies may either represent short polarity reversals or geomagnetic intensity fluctuations; it is important that the correct alternative be determined.

One thing that has been learned by bitter experience in the recent study of magnetic excursions is that it is absolutely essential that any apparent event be replicable. We consider that a site selected as suitable for this study should be cored three times. We have no doubt that sites will be located which will be of prime interest for high-resolution climatic and other studies, and that replicate sampling of a single site will be justified from several points of view.

These records additionally will be invaluable for extending studies of secular variation, which are presently concentrated in lake sediments covering only about 10^4 yr.

F.4 Plate Motions

Up to now, the reconstruction of late Mesozoic and Cenozoic plate positions has been based on two important data sets. The mapped marine magnetic anomalies enable oceanic plates, together with attached continents to be placed relative to one another at the time of a particular anomaly by removing all the new crust that has formed since that time. Paleopole positions, based on the paleomagnetic study of exposed rocks, supplement this information for relative plate positions and provide a paleolatitudinal framework. Paleopole data are generally lacking for oceanic plates that are not attached to continents, (e.g., the Pacific plate) and there is uncertainty in correlating the continental rocks examined with a particular magnetic anomaly. Paleomagnetic measurements in deep-sea sediment can, in principle, provide a continuous record of the paleolatitude of a site, or if properly oriented azimuthally, pole positions for that plate. Moreover, uncertainty in the temporal relation between the pole position and the contemporaneous magnetic anomaly is removed by magnetostratigraphic correlations. Although there is already a certain amount of data available for the Pacific plate, it is clear that there is a serious need for good, continuous data sets (see, for example, Suarez and Molnar, 1980; Fig. 18).

A few estimates of paleolatitude have been made on the basis of DSDP materials (e.g., Peirce, 1976). Recently L. Tauxe (pers. commun.) has shown the possibility of obtaining accurate and continuous information from magnetic studies on the sediment recovered from an HPC-cored site. We would recommend that two sites as widely separated as possible on each plate be sought for this purpose so that the paleopole estimates for the plate can be checked for consistency. Since many of the potential systematic errors would be likely to be correlated downhole (azimuth orientation error, departure from verticality), each site should be cored twice.

F.5 Reversal Timescales

The current magnetic reversal timescales are the result of a complex interplay between magnetostratigraphy, biostratigraphy, and radiometric dating. The intercorrelation of the various biostratigraphic zonations and the paleomagnetic record is proceeding rapidly at present (Fig. 19). However, beyond the past few million years it is generally the case that the magnetostratigraphic record is only related to the radiometric data via a series of biostratigraphic links

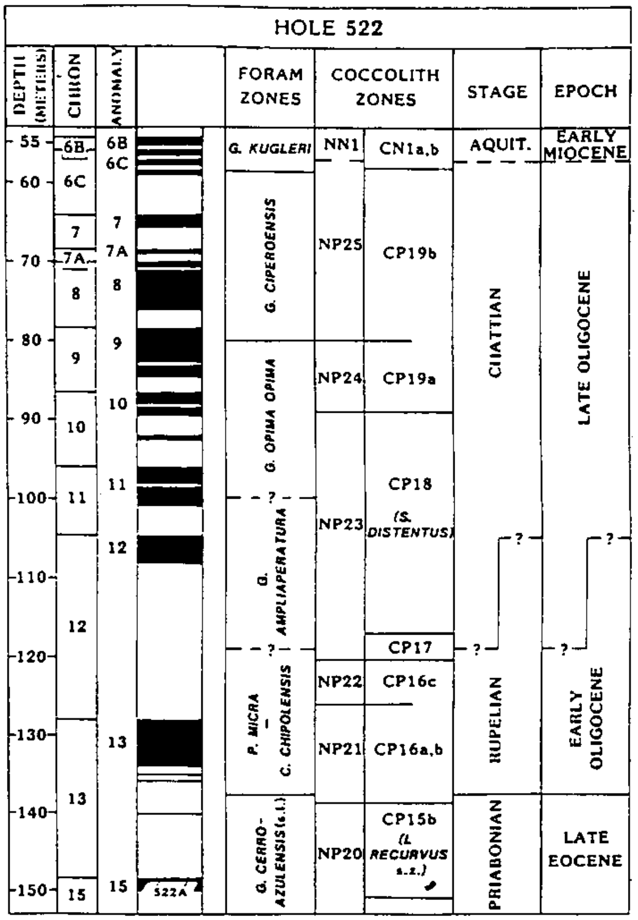


Figure 19. An example of the direct and detailed tie between biostratigraphic zones and the paleomagnetic reversal scale, from hydraulic piston cores taken in the South Atlantic during DSDP Leg 73. (Leg 73 Scientific Staff, pers. commun.).

whose accuracy and precision cannot be meaningfully specified. To a large extent this is due to the fact that the radiometric dates are related to continental rocks which although important as type sections, lack the appropriate information for detailed correlation with deep-sea sequences. An additional, intervening factor is the possibility of deriving a magnetic timescale directly, with a minimum number of radiometric calibration points, by using the magnetic anomaly record of the sea floor and assuming a uniform rate of spreading. It is very difficult to evaluate discrepancies between these timescales, although they are important both for geochronology and for the study of sea-floor spreading. In part this situation will naturally evolve as more data becomes available. However, we propose a program of direct calibration.

The only material older than the past million years in deep-sea sediment that is amenable to radiometric age dating is volcanic ash. By planning drilling in appropriate areas, it should be possible to recover ash layers from the Paleogene and put a direct radiometric scale on a critical part of the record of magnetic polarity. Donn and Ninkovich (1980) have shown that there was extensive explosive volcanism in the North Atlantic, especially during the middle Eocene, and Paleogene ash layers are also reported from the Caribbean. It is likely that a significant contribution to the problem also could be made by a greater attention to the dating of deep-sea basalts and ash layers in the sediments close to the basalt.

Another approach to this problem is to use the well-established astronomical variations in the angle of the earth's rotational axis with respect to the plane of the orbit and the precession with reference to the moving ecliptic as a direct measure of the passage of time (Shackleton, 1981). It is well established that the effect of these variations on climate during the Pleistocene is easily detected (Hays et al., 1976), providing an independent astronomical check of the age of the Brunhes/Matuyama boundary (Kominz et al., 1979). It is also well known that sedimentological variations in the appropriate frequency range are observed in a wide variety of sedimentological settings in much of the geological column. By making very careful analysis of any parameter (stable isotopic composition, percentage carbonate, etc.) that reflects these changes, in conjunction with paleomagnetic measurement, it will be possible to measure the time interval between successive reversals (Moore et al., 1982) and so to measure the rate of plate motion directly, independent of determinations of radiometric age. For this purpose, Cenozoic sequences at least one or two million years long, accumulated at a rate of at least 2 cm/10^3 yr (in order to adequately resolve the precessional component), must be recovered with complete overlap between successive HPC deployments.

G. TARGET AREAS FOR SHALLOW CORING (HPC) AND DEEP DRILLING

G.1 Special Sampling Strategies: Depth Transects for Oceanic Gradients

We propose to study the changes and events in the oceanic atmosphere and biosphere during the Cenozoic and Mesozoic by establishing the oceanographic and biotic gradients at key locations in the oceans. We plan to accomplish this goal by drilling a number of transects, each composed of a series of sites, similar to the transects designed for the 1981-83 DSDP program.

Because surface circulation is critical in the transport of energy from low to high latitudes, it is important to establish both latitudinal and meridional gradients for surface waters. These gradients will be determined by analyzing transects of deep-sea sediments across oceans or oceanic boundary zones. Bottom waters change gradually in their character as they move away from their source and show gentle gradients over wide areas of the ocean. We propose to study them in, or close to, the areas of their formation. The condition of the bottom water will also be examined in depth transects designed to investigate vertical oceanographic gradients. These reflect the stratification of the oceans and are associated with depth-specific sedimentary facies, microfossils, stable isotopes, and geochemical properties. Important vertical gradients of interest include the pycocline, oxygen minimum zone, and the CCD; all of these have varied with the different oceanic states.

G.2 Areas for Shallow Coring (HPC)

HPC coring in the following area (Fig. 20) would establish the global network of cores necessary to attack the major problems listed in the previous sections. A brief listing of some of the objectives is appended to each region. The listing is not meant to be exhaustive nor restrictive but is meant to be examples of the scientific objectives which might be pursued in each region.

Indian Ocean

a. Kerguelen Plateau: high-latitude fertility, depth/dissolution profile, evolutionary studies.
b. 40°-50°N, mid-ocean ridge: surface-ocean thermal response, frontal oscillations, evolutionary studies.
c. Central equatorial: equatorial fertility, surface circulation.
d. Western Arabian Sea: monsoonal upwelling; surface circulation.

Atlantic Ocean

a. Equatorial and Caribbean: equatorial upwelling, cross-equatorial heat flux, evolutionary studies.
b. Labrador Sea: surface-ocean thermal response, initiation of ice rafting and low-salinity Arctic outflow, meltwater outflow.
c. Gulf of Mexico: meltwater outflow history.
d. Mediterranean Sea: salinity response, sapropels, evaporites, Nile outflow.
e. Agulhas Plateau: surface-ocean thermal response, heat flux from Indian to Atlantic Ocean, northward advection of subantarctic water, eastern boundary current upwelling.
f. 40°-50°N: subantarctic thermal response, frontal oscillations, oceanic thermal response.
g. Angola margin: coastal upwelling, anoxic sediments, surface-ocean thermal response.

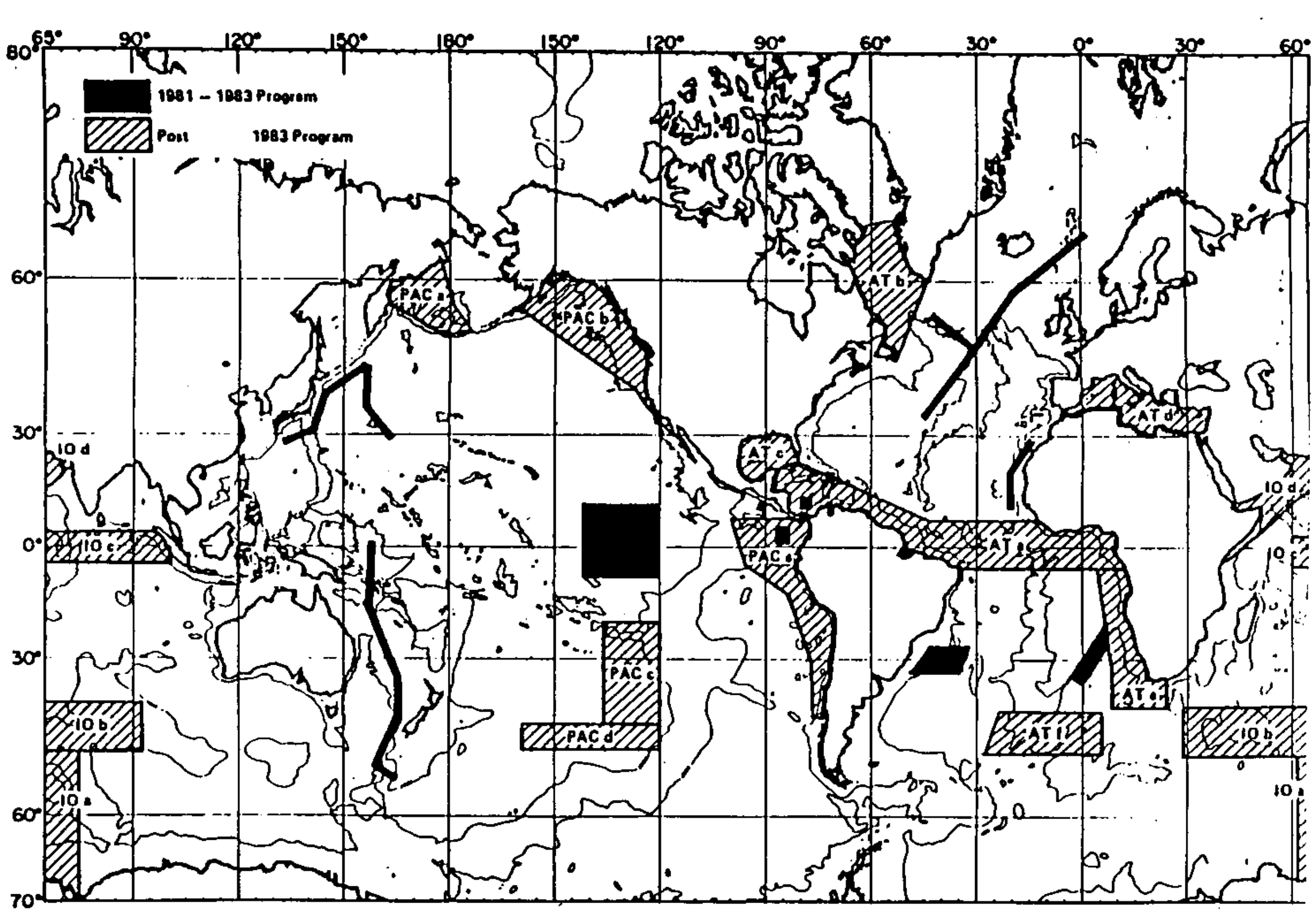


Figure 20. Areas proposed for hydraulic piston coring.

h. Northwestern Africa: eolian sedimentation.

Pacific Ocean

a. Southwest Bering Sea: surface-ocean thermal response, high-latitude fertility, evolutionary studies.

b. Northeast Pacific: surface-ocean thermal response, initiation of glaciation.

c. West flank of East Pacific Rise: depth profile for CCD variations under central gyre.

d. Subantarctic, north flank of East Pacific Rise: surface-ocean thermal response, frontal oscillations, high-latitude fertility.

e. Peru-Chile Currents: fertility variations in eastern boundary currents, northward advection of subantarctic water, cross-equatorial flow.

G.3 Areas for Deep Drilling

Most of the major Paleogene and Mesozoic objectives outlined in earlier sections will require drilling in addition to shallow coring to obtain the required sediment samples. A brief listing of the major objectives is appended to each area (see Fig. 21).

Indian Ocean

a. Kerguelen Plateau: Paleogene oceanic and climatic states, depth transect for vertical gradients, southern hemisphere glaciation, high-latitude biotic history.

b. Exmouth Plateau: Paleogene and Mesozoic depth transect for vertical gradients, closure of the Indonesian passageway.

c. Indian Ocean Transect: Paleogene and Mesozoic depth transect for vertical gradients, Mesozoic gateways and deep circulation, Mesozoic anoxic sediments, Cretaceous-Tertiary boundary.

d. Agulhas Plateau: Paleogene and Mesozoic gateways and depth transect for vertical gradients, Mesozoic deep circulation, Mesozoic anoxic sediments, Cretaceous-Tertiary boundary.

e. Northwestern Australia: Paleogene gateways, deep circulation, depth transect for vertical gradients.

Atlantic Ocean

a. Voring Plateau: Norwegian Sea: Paleogene and Mesozoic deep circulation, high-latitude glaciation, biotic history of high latitudes, Mesozoic anoxic sediments, Cretaceous-Tertiary boundary.

b. Labrador Sea: Neumann Basin: Paleogene oceanic and climatic states, depth transects for vertical gradients, deep circulation, high-latitude biotic history.

c. Sierra Leone Rise: Paleogene and Mesozoic gateways and depth transect for vertical gradients, early Mesozoic ocean and climate, Mesozoic anoxic sediments.

d. Argentine Basin: Falkland Plateau, early

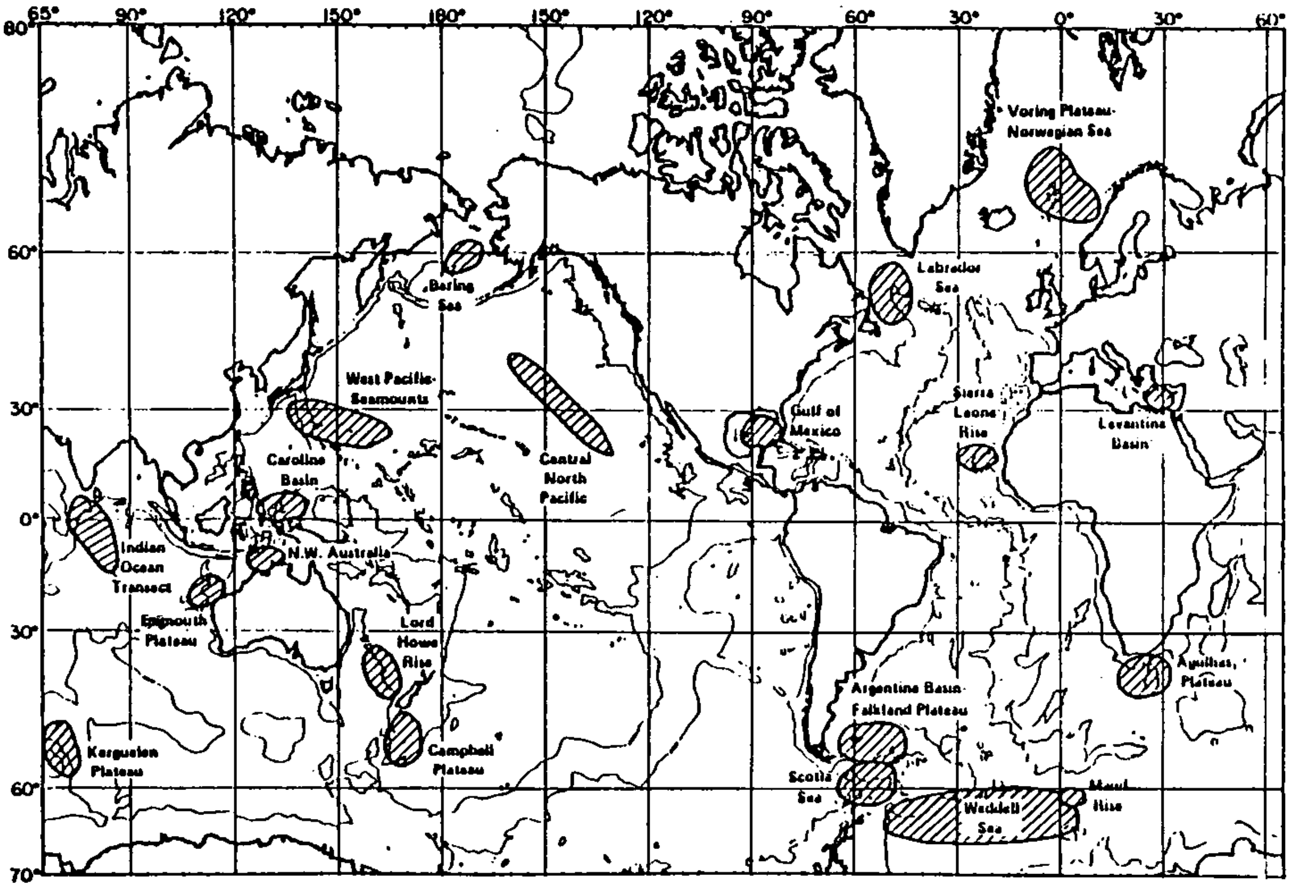


Figure 21. Areas proposed for shallow coring (HPC) and deep drilling.

Mesozoic climatic and oceanic states, Mesozoic circulation, Cretaceous-Tertiary boundary, Paleogene gateways.

e. Scotia Sea: Paleogene gateways, deep circulation.
f. Weddel Sea region: Paleogene and Mesozoic history of high-latitude glaciation, deep-ocean circulation, depth transect for vertical gradients, high-latitude biotic history, Cretaceous-Tertiary boundary.
g. Maud Rise: Paleogene depth transect for vertical gradients, gateway, history of high-latitude glaciation.
h. Gulf of Mexico: early Mesozoic ocean and climate; depth transects for vertical gradients.

Mediterranean Sea

a. Eastern basin (Levantine Basin): early Mesozoic gateways, Paleogene and late Mesozoic deep circulation; Mesozoic anoxic sediments.

Pacific Ocean

a. Western Pacific; early Mesozoic history of the superocean, Mesozoic paleogeography and hypsogeography, Mesozoic depth transect for vertical gradients, Mesozoic circulation, Cretaceous-Tertiary boundary.
b. Bering Sea: Paleogene and Mesozoic history of high-latitude glaciation, Mesozoic circulation, depth transect for vertical gradients, Cretaceous-Tertiary boundary, biotic history in high latitudes.
c. Caroline Basin: Paleogene gateway and history of deep circulation.
d. Philippine Sea: Neogene orbital response.
e. Central North Pacific transect: eolian sedimentation and terrestrial influence in the deep ocean.
f. Campbell Plateau: Paleogene and Mesozoic of high-latitude oceanography.
g. Peru Margin: anoxic sedimentation, coastal upwelling.

H. SUMMARY

Although this paper contains a discussion of many scientific problems and their possible solutions with the aid of drilling in many regions (and has left many more questions undiscussed), three themes have recurred in many sections.

First, in the next phase of ocean drilling maximum attention should be given to the optimal recovery of undisturbed sediment. The advent of the HPC has dramatically increased the average "percentage recovery" quoted, and it has also dramatically increased the percentage of undisturbed sediment recovered, from near zero to in the region of 50%. Hopefully the Extending Core Barrel (XCB) will make an equivalent contribution towards the recovering of difficult material deeper in the section, especially in chert-chalk sequences. Many of the problems that have been discussed in this paper require attention to recovery of undisturbed sediment for their solution.

A second theme presented in discussions of several of the scientific problems has been the need for global coverage. This is not to be interpreted as a call for a global grid of evenly spaced sites but rather for a well-thought-out drilling plan which focuses on specific areas in which suitable horizontal and vertical transects can be used to trace long-term changes in the Earth's systems. The fact that all elements of these systems are global in nature requires that our sample coverage be global if we are to develop a clear understanding of their histories and interactions.

Of all the regions discussed in this report, the high latitudes have received particular emphasis and represent the third theme. The polar regions are critical to the understanding of climatic changes which have had a global impact on the biosphere, the atmosphere, the oceans, and ultimately the lithosphere. The polar regions are particularly inhospitable to man and machine; the small amount of material so far recovered has been of critical importance in our reconstructions, and adequate recovery in the future probably represents one of the greatest technical challenges in the drilling program.

We see the following questions as of primary interest over the next decade:

a. Paleoceanography

1. How did the Mesozoic "Superocean" operate? What were the inter-relationships between this superocean and the evolving and initially restricted marginal proto-oceans?
2. What is the history of the polar seas and their influence on the world ocean?
3. How has the vertical and horizontal structure of the oceans changed with the evolution of their solid boundaries?

b. Paleoclimatology

1. How has the response of global climate to variations in the Earth-Sun orbital system changed as the internal boundary conditions have varied?
2. How were the polar regions maintained at such high temperatures during significant parts of Earth history?

c. Evolution

1. How does evolutionary change at the level of species and entire biotas in the marine realm proceed in time and space?
2. How (if at all) have external factors affected evolutionary processes in the marine realm?

d. Magnetic Field

1. What has been the three-dimensional pattern of the Earth's magnetic field during times of reversal and change? What were the underlying mechanisms?
2. What has been the history of change and spectrum of variability of the Earth's magnetic field?

I. REFERENCES

Arthur, M.A., 1979, North Atlantic Cretaceous black shales; the record at Site 398 and a brief comparison with other occurrences, *in* Sibuet, J.-C., Ryan, W.B.F., et al., Initial reports of the Deep Sea Drilling Project, Vol. 47, Part 2: Washington, D.C., U.S. Govt. Printing Office, p. 719-751.

Arthur, M.A., and Schlanger, S.O., 1979, Cretaceous "oceanic anoxic events" as causal factors in development of reef-reservoired giant oil fields: Am. Assoc. Petroleum Geologists Bull., v. 63, p. 870-885.

Barron, E.J., Thompson, S.L., and Schneider, S.H., 1981, An ice-free Cretaceous? Results from climate model simulations: Science, v. 212, p. 501-508.

Barron, E.J., and Washington, W.M., 1982, The atmospheric circulation during warm geologic periods: Nature (in press).

Benson, R.A., 1975, The origin of the pyschrosphere as recorded in changes of deep-sea ostracod assemblages: Lethaia, v. 8, p. 69.

Berger, W.H., 1977, Carbon dioxide excursions and the deep-sea records: Aspects of the problem, *in* Andersen, N.R., and Malahoff, A., eds., The fate of fossil fuel CO_2 in the oceans: New York, Plenum Press, p. 505-542.

Berger, W., 1979, Impact of deep-sea drilling on paleoceanography, *in* Talwani, M., Hay, W., and Ryan, W., eds., Deep drilling in the Atlantic Ocean: Continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 1-26.

Berger, W.H., 1970, Biogenous deep-sea sediments: Fractionation by deep-sea circulation: Geol. Soc. America Bull., v. 81, p. 1385-1402.

Berger, W.H., Vincent, E., and Thierstein, H.R., 1981, The deep-sea record: Major steps in Cenozoic ocean evolution, *in* Warme, J., Douglas, R.G., and Winterer, E., eds., The Deep Sea Drilling Project, A decade of progress: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 32, p. 169-179.

Berger, W.H., and Winterer, E.L., 1974, Plate stratigraphy and the fluctuating carbonate line, *in* Hsu, K.J., and Jenkyns, H.C., eds., Pelagic sediments: On land and under the sea, Internatl. Assoc. Sedimentologists Spec. Pub. No. 1: Oxford, England, Blackwell Scientific, p. 11-48.

Biscaye, P., 1965, Mineralogy and sedimentation of recent deep-sea clay in the Atlantic Ocean and adjacent seas and oceans: Geol. Soc. America Bull., v. 76, p. 803-832.

Brass, G.W., Hay, W.W., Halser, W.T., Peterson, W.H., Saltzman, E., Sloan, J.L., II, and Southam, J.R., 1982, Ocean circulation, plate tectonics and climate: Nat. Res. Council Spec. Pub., Geophys. Study Comm. (in press).

Bukry, D., 1981, Cretaceous Arctic silicoflagellates: Geo-Marine Letters, v. 1, p. 57-63.

Cande, S.C., and LaBrecque, J.L., 1974, Behaviour of the Earth's palaeomagnetic field from small scale marine magnetic anomalies: Nature, v. 247, p. 26-28.

Chamley, H., 1979, North Atlantic clay sedimentation and paleoenvironment since the Late Jurassic, *in* Talwani, M., Hay, W., and Ryan, W.B., eds., Deep drilling results in the Atlantic Ocean: Continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 342-361.

Cox, A., 1975, The frequency of geomagnetic reversals and the symmetry of the non-dipole field: Rev. Geophysics and Space Physics, v. 13, p. 31-51.

Crough, S.T., 1978, Thermal origin of mid-plate hotspot swells: Royal Astron. Soc. Geophys. Jour., v. 55, p. 451-469.

Davies, T.A. and Worsely, T.R., 1981, Paleoenvironmental implications of oceanic carbonate sedimentation rates, *in* Warme, J., Douglas, R.G., and Winterer, E., eds., The Deep Sea Drilling Project, A decade of progress: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 32, p. 169-179.

Donn, W.L., and Ninkovich, C.D., 1980, Rate of Cenozoic volcanism in the North Atlantic Ocean: Jour. Geophys. Research, v. 85, p. 5455-5460.

Douglas, R.G., and Savin, S.M., 1975, Oxygen and carbon isotope analyses of Tertiary and Cretaceous microfossils from Shatsky Rise and other sites in the North Pacific Ocean, *in* Larson, R.L., Moberly, R., et al., Initial reports of the Deep Sea Drilling Project, Vol. 32: Washington, D.C., U.S. Govt. Printing Office, p. 509-520.

Douglas, R.G., and Savin, S.M., 1982, The marine oxygen isotope record and global sea level fluctuation: Marine Micropaleontology (in press).

Douglas, R.G., and Woodruff, F., 1981, Deep sea benthic foraminifera, *in*, Emiliani, C., ed., The sea, Vol. VII: New York, John Wiley and Sons, Inc., Interscience Publishers, p. 1233-1327.

Eldredge, N., and Gould, J., 1972, Punctuated equilibria: An alternative to phyletic gradualism, *in* Schopf, T.J.M., ed., Models in paleobiology: San Francisco, California, Freeman, Cooper, and Co., p. 82-115.

Eldredge, N., and Cracraft, J., 1980, Phylogenetic patterns and the evolutionary process: Method and theory in comparative biology: New York, Columbia University Press, 349 p.

Emiliani, C., and Geiss, J., 1957, On glaciations and their causes: Geol. Rundschau, v. 46, p. 576-601.

Endler, J., 1977, Geographic variation, speciation and clines, Princeton Univ. Monogr. in Population Biology No. 10: Princeton, New Jersey, Princeton University Press, 246 p.

Fuller, M., Williams, I., and Hoffman, K.A., 1979, Paleomagnetic records of geomagnetic field reversal and the morphology of the transitional field: Rev. Geophysics and Space Physics, v. 17, p. 179-203.

Gardner, J., and Prell, W., 1980, Leg 68/HPC: JOIDES Jour., v. 6, p. 16-25.

Ghil, M., 1981, Internal climatic mechanisms participating in glaciation cycles, *in* Berger, A., ed., Climatic variations and variability: Facts and theories: Dordrecht/Boston/London, D. Reidel Publishing Co., p. 539-557.

Habib, D., 1979, Sedimentary origin of North Atlantic Cretaceous palynofacies, *in* Talwani, M., Hays, W., and Ryan, W., eds. Deep drilling results in the Atlantic Ocean: Continental margins and paleoenvironment, Maurice Ewing Series, Vol. 3: Washington, D.C., American Geophysical Union, p. 420-437.

Haq, B.U., Lohmann, G.P., and Wise, S.W., 1977, Calcareous nannoplankton biogeography and paleoclimatic implications: Cenozoic of the Falkland Plateau (DSDP Leg 36) and Miocene of the Atlantic Ocean, *in* Barker, P.F., Dalziel, I.W.D. et al., Initial reports of the Deep Sea Drilling Project, Vol. 36, Washington, D.C., U.S. Govt. Printing Office, p. 745-759.

Haq, B.U., 1980, Biogeographic history of Miocene calcareous nannoplankton and paleoceanography of the Atlantic Ocean: Micropaleontology, v. 26, p. 414-443.

Harrison, C.G.A., 1969, What is the true rate of reversals of the Earth's magnetic field?: Earth and Planet. Sci. Letters, v. 6, p. 186-188.

Harrison, C., 1980, Reply to "Comment on Mesozoic evolution of the Antarctic Peninsula and the southern Andes:" Geology, v. 7, p. 374-378.

Harrison, C.G.A., and Ramirez, E., 1975, Areal coverage of spurious reversals of the Earth's magnetic field: Jour. Geomagnetism and Geoelectricity, v. 27, p. 139-151.

Hays, J.D., Imbrie, J., and Shackleton, N.J., 1976, Variations in the earth's orbit: Pacemaker of the ice ages: Science, v. 194, p. 1121-1132.

Heath, G.R., 1974, Dissolved silica and deep-sea sediments, *in* Hay, W.W., ed., Studies in paleo-oceanography: Soc. Econ. Paleontologists and Mineralogists Spec. Pub. 20, p. 77-93.

Hoffman, K.A., 1977, Polarity transition records and the geomagnetic field: Science, v. 196, p. 1329-1332.

Kennett, J.P., 1981, Cenozoic paleoceangraphy: Marine Micropaleontology, v. 6, p. 5-6.

Kominz, M.A., Heath, G.R., Ku, T.L., and Pisias, N.G., 1979, Brunhes time scales and the interpretation of the climatic change: Earth and Planet. Sci. Letters, v. 20, p. 315-324.

Leinen, M., and Heath, G.R., 1981, Sedimentary indicators of atmospheric activity in the northern hemisphere during the Cenozoic: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 36, p. 1-21.

Malmgren, B.A., and Kennett, J.P., 1981, Phyletic gradualism in a late Cenozoic planktonic foraminiferal lineage; DSDP Site 284, southwest Pacific: Paleobiology, v. 7, p. 230-240.

McIntyre, A., 1967, Coccoliths as paleoclimatic indicators of Pleistocene glaciation: Science, v. 158, p. 1314-1317.

McIntyre, A., Kipp, N.G., Bé, A.W.H., Crowley, T., Kellogg, T., Gardner, J.V., Prell, W., and Ruddiman, W.F., 1976, Glacial North Atlantic 18,000 years ago: A CLIMAP reconstruction, *in* Cline, R.M., and Hays, J.D., eds., Investigation of late Quaternary paleoceanography and paleoclimatology: Boulder, Colorado, Geol. Soc. America Memoir 145, p. 43-76.

Moore, T.C., Pisias, N.G., and Dunn, D., 1982, Pacific carbonate variations in the Quaternary and late Miocene: A spectral comparison: Marine Geology (in press).

Moore, T.C., Pisias, N.G., and Heath, G.P., 1977, Climatic changes and lags in Pacific carbonate preservation, sea-surface temperature, and global ice volume, in Andersen, N., and Malahoff, A., eds., The fate of fossil fuel CO_2 in the oceans: New York, Plenum Press, p. 145-165.

Morner, N.A., 1980, Pliocene stratigraphy and paleoclimatology in Europe in relation to global paleoceanographic changes and the initiation of glaciations: International Geological Congress, 26th, Paris, Abstracts, v. 2, p. 676.

Morner, N.A., 1981, Revolutions in Cretaceous sea level analysis: Geology, v. 9, p. 344-346.

Opdyke, N.D., Kent, D.V., and Lowrie, W., 1973, Details of magnetic polarity transitions recorded in a high deposition rate deep-sea core: Earth and Planet. Sci. Letters, v. 20, p. 315-324.

Parsons, B., and Sclater, J.G., 1977, An analysis of the variations of ocean floor bathymetry and heat flow with age: Jour. Geophys. Research, v. 82, p. 803-827.

Peirce, J.W., 1976, Assessing the reliability of DSDP paleolatitudes: Jour. Geophys. Research, v. 81, p. 4173-4187.

Peterson, W.H., Brass, G.W., and Southam, J.R., 1981, The formation of warm saline bottom water in ancient oceans: Ocean Modelling, v. 38, p. 1-7.

Phillips, J.D., 1977, Time variation and asymmetry in the statistics of geomagnetic reversal sequences: Jour. Geophys. Research, v. 82, p. 835-843.

Pisias, N.G., and Moore, T.C., 1981, The evolution of Pleistocene climate: A time series approach: Earth and Planet. Sci. Letters, v. 52, p. 450-458.

Pitman, W., 1978, Relationship between eustacy and stratigraphic sequences at passive margins: Geol. Soc. America Bull., v. 89, p. 1389-1403.

Prell, W., Gardner, J., et al., 1982, Initial reports of the Deep Sea Drilling Project, Vol. 68: Washington, D.C., U.S. Govt. Printing Office (in press).

Prospero, J.M., 1981, Eolian transport to the world ocean, *in* Emiliani, C., ed., The sea, Vol. 7: New York, Wiley and Sons, p. 801-874.

Rea, D.K., and Janecek, T.R., 1981, Late Cretaceous history of eolian deposition in the Mid-Pacific Mountains, central North Pacific Ocean: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 36, p. 55-67.

Roth, P., 1978, Cretaceous nannoplankton, biostratigraphy and paleoceanography of the northwestern Atlantic, *in* Benson, W.E., Sheridan, R.E., et al., Initial reports of the Deep Sea Drilling Project, Vol. 44: Washington, D.C., U.S. Govt. Printing Office, p. 731-759.

Saemundsson, K., Kristjansson, L., McDougall, I., and Watkins, N.D., 1980, K-Ar dating, geological and paleomagnetic study of a 5-km lava succession in northern Iceland: Jour. Geophys. Research, v. 85, p. 3628-3646.

Savin, S.M., Douglas, R.G., Keller, G., Killingley, J.S., Shaughnessy, L., Sommer, M.A., Vincent, E., and Woodruff, F., 1981, Miocene benthic foraminiferal isotope records: A synthesis: Marine Micropaleontology, v. 6, p. 423-450.

Schlanger, S.O., and Jenkyns, H.C., 1976, Cretaceous oceanic anoxic events; causes and consequences: Geol. Mijnbouw, v. 55, p. 179-184.

Schlanger, S.O., Jenkyns, H.C., and Premoli-Silva, I., 1981, Volcanism and vertical tectonics in the Pacific Basin related to the global Cretaceous transgression: Earth and Planet. Sci. Letters, v. 52, p. 435-449.

Schlanger, S.O., and Premoli-Silva, I., 1981, Tectonic, volcanic, and paleogeographic implications of redeposited reef faunas of Late Cretaceous and Tertiary age from the Nauru Basin and the Line Islands, *in* Larson, R.L., Schlanger, S.O., et al., Initial reports of the Deep Sea Drilling Project, Vol. 61: Washington, D.C., U.S. Govt. Printing Office, p. 817-827.

Scholle, P., and Arthur, M., 1980, Carbon-isotope fluctuations in Cretaceous pelagic limestone: Potential stratigraphic and petroleum exploration tool: Am. Assoc. Petroleum Geologists Bull., v. 64, p. 67-87.

Shackleton, N.J., and Opdyke, N.D., 1976, Oxygen-isotope and paleomagnetic stratigraphy of Pacific core V28-239: Late Pliocene to latest Pleistocene, *in* Cline, R.M., and Hays, J.D., eds., Investigation of Late Quaternary paleoceanography and paleoclimatology: Boulder, Colorado, Geol. Soc. America Memoir 145, p. 449-464.

Shackleton, N.J., and Opdyke, N.D., 1977, Oxygen isotope and paleomagnetic evidence for early Northern Hemisphere glaciation: Nature, v. 270, p. 216-219.

Shackleton, N.J., 1981, The future of the Cenozoic timescale: European Union of Geosciences Abstract R-40.

Shackleton, N.J., and Boersma, A., 1981, The climate of the Eocene ocean: Jour. Geological Soc. London, v. 138, p. 153-157.

Sheehan, P., 1977, Species diversity in the Phanerozoic a reflection of labor by systematists?: Paleobiology, v. 3, p. 325-329.

Smith, A.G., and Briden, J.C., 1977, Mesozoic and Cenozoic paleocontinental maps, *in* Cambridge Earth science series: Cambridge, England, Cambridge University Press, 63 p.

Suarez, G., and Molnar, P., 1980, Paleomagnetic data and pelagic sediment facies and the motion of the Pacific plate relative to the spin axis since the Late Cretaceous: Jour. Geophys. Res., v. 85, p. 5257-5280.

Thierstein, H., Brumsack, H.J., and Roth, P., 1981,, Mid-Cretaceous black shales and ocean fertility: Geol. Soc. America Abstracts with Programs, v. 13, no. 7, p. 565.

Thompson, S.L., and Barron, E.J., 1981, Comparison of Cretaceous and present earth albedos: Implications for the causes of paleoclimates: Jour. Geology, v. 89, p. 143-167.

Vail, P.R., and Hardenbol, J., 1979, Sea level changes during the Tertiary: Oceanus, v. 22, p. 71-79.

Vail, P.R., Mitchum, R.M., Jr., and Thompson, S., III, 1977, Seismic stratigraphy and global changes of sea level; Part 3, Relative changes of sea level from coastal onlap, *in* Payton, C.E., ed., Seismic stratigraphy; applications to hydrocarbon exploration: Tulsa Oklahoma, Amer. Assoc. Petroleum Geologists Memoir 26, p. 63-81.

Valet, J.P., and Laj, C., 1981, Paleomagnetic record of two successive Miocene geomagnetic reversals in western Cretaceous: Earth and Planet. Sci. Letters, v. 54, p. 53-63.

Van Andel, T.H., Heath, G.R., and Moore, T.C., Jr., 1975 Cenozoic history and paleoceanography of the central equatorial Pacific Ocean: A regional synthesis of Deep Sea Drilling Project data: Boulder, Colorado, Geol. Soc. America Memoir 143, 134 p.

Van Andel, T.H., Thiede, J., Sclater, J.C., and Hay, W.W., 1977, Depositional history of the south Atlantic Ocean during the last 125 million years: Jour. Geology, v. 85, p. 651-698.

Watkins, N.D., McDougall, I., and Kristjansson, L., 1977, Upper Miocene and Pliocene geomagnetic secular variation in the Borgarfjordur area of western Iceland: Royal Astron. Soc. Geophys., Jour., v. 49, p. 609-632.

Watkins, N.D., and Walker, G.P., 1977, Magnetostratigraphy of eastern Iceland: Am. Jour. Sci., v. 277, p. 513-584.

Winterer, E.L., 1976, Bathymetry and regional tectonic setting of the Line Islands chain, *in* Schlanger, S.O., Jackson, E.D., et al., Initial reports of the Deep Sea Drilling Project, Vol. 33: Washington, D.C., U.S. Govt. Printing Office, p. 731-747.

TOOLS, TECHNIQUES, AND ASSOCIATED STUDIES

A. INTRODUCTION

The question asked of Working Group V was: "How can ocean drilling and associated scientific programs be organized and co-ordinated to attack the most important scientific problems in the most orderly and productive way?" We approached this question specifically with the period 1984-1990 in mind. Our deliberations fell under three main headings: Drilling Technology, Logging and Downhole Experiments, and Related Geophysical and Geological Studies.

B. DRILLING TECHNOLOGY

B.1 Riser vs. Riserless Drilling

Before getting involved with specific drilling platforms, some general points need to be made about these two techniques. Riser drilling in the offshore oil industry has now progressed to a water depth of 1500 meters (Parkinson & Saren, 1981). Progress to greater water depths continues and drilling in oceanic depths (5000 meters +/- 2000 meters) is a reasonable ultimate objective. However, the extension of technology beyond current practice required to reach such depths is large and progress towards deeper water will be gradual. Riser drilling in a water depth of 2700 meters is unlikely to be achieved before the second half of the 1980's. One must conclude that any riser drilling program for scientific purposes prior to 1990 cannot be a truly oceanic program but will be restricted largely to the shallower waters of the oceans' margins.

To this technical point must be added its organizational consequences. If all the resources of the United States for scientific ocean drilling were put behind the development of riser drilling, a hiatus of some five years in scientific ocean drilling would result in the second half of the 1980's. Furthermore, many of the IPOD countries, certainly France, the United Kingdom, and probably others, would not be interested in a program focused almost entirely on the continental margins of the United States. It is clear, therefore, that if scientific ocean drilling is to maintain its momentum, it will depend on a program of riserless drilling continuing through the period 1984-89. The question of whether the scientific problems exist to justify such a five-year program is being considered by other working groups. Here we are concerned with whether riserless drilling has the technical potential to solve these problems.

B.2 Drilling Platforms

At the time of the COSOD meeting hard information on the costs of different drilling platforms was not available. However, it was clear that cost considerations would rule out the construction of a new drilling vessel and that the choice of platform for drilling beyond 1983 would rest between *Glomar Challenger*, the pioneering workhorse of the Deep Sea Drilling Project for the last 13 years, and the *Glomar Explorer*, a ship already owned by the U.S. Government. The following technical features are relevant in making a comparison between the two ships:

1. The *Glomar Explorer* has a displacement six times greater than the *Glomar Challenger* and a draft that is almost double. These characteristics make it a very stable platform that would enable drilling operations to continue when on *Glomar Challenger* they would have to shut down.
2. Greatly increased laboratory and living facilities on the *Glomar Explorer* would permit an increased number of scientists to participate in the cruises, offering the possibility of expanding the membership in IPOD. In addition, there would be room to accommodate technicians needed for proposed downhole instrumentation programs and engineers for testing new devices to support a continuing program designed to improve the drilling and coring capabilities.
3. The *Glomar Explorer* can be ice-strengthened permitting transit in small ice-block conditions to drilling sites in high latitudes, a modification not feasible on the *Glomar Challenger*.
4. A large mud capacity on the *Glomar Explorer* could be important if drilling without mud return proves viable and is essential if a mud-return system is adopted.
5. A longer drill string will be available for use in deep-water targets, but use of this capability is dependent on drill-string design as well as smaller motion expected for the larger ship.

The size of the *Glomar Explorer* has its disadvantages too since it cannot transit the Panama Canal, and the choice of ports and drydocking facilities is limited. Both vessels would need a refit requiring the *Glomar Challenger* to be in dry dock from 1 to 2 months and the *Glomar Explorer* from 12 to 18 months.

The choice of vessel will depend greatly on economic factors not considered here. But it will also depend on the nature and duration of the program of scientific ocean drilling which is envisaged. If we were just concerned with a short-term program in the 1980's — consisting of many holes of limited penetration, possibly with increased emphasis on downhole instrumentation and experiments — then *Glomar Explorer* would have little to offer over what *Glomar Challenger* already provides. If, however, the 1983-88 program puts more emphasis on fewer, deeper holes — possibly drilled with mud without return and spending longer times on hole — *Glomar Explorer* begins to look more useful.

But the advantages of *Glomar Explorer* become obvious only if scientific ocean drilling is envisaged as a long-term, developing activity stretching well into the 1990's. By 1990 *Glomar Challenger* will have reached the end of her life (22 years), whereas *Glomar Explorer's* life will be only half over. Over the years the growth potential of *Glomar Explorer* would allow development of new drilling techniques — the use of a full riser, mud systems, the deployment of a large-bore (15cm) hydraulic piston corer for geotechnical sampling, the deployment of heavy equipment — none of which are feasible with *Glomar Challenger*.

The unanimous view of the COSOD meeting was that scientific ocean drilling is a long-term endeavor and that, therefore, *Glomar Explorer* is the preferred vessel to achieve our long-term goals.

B.3 The Limitations and Potential of a Program of Riserless Drilling

The *Glomar Challenger*, while achieving outstanding success, has suffered from a number of persistent limitations that are of a technical, engineering, programatic and organizational nature. The following discussion addresses the technical limitations of the past program of riserless drilling and the potential for future expectations.

Penetration. The deepest penetration of the ocean floor achieved to date was at Hole 398D (Leg 47), where 1740 meters of sediment was penetrated under 3910 meters of water off Portugal in 1976. The greatest penetration of the oceanic basement was 1075 meters, for a total sub-bottom depth of 1350 meters, at Hole 504B (Legs 70 and 83) in the Costa Rica Rift in 1979 and 1981. It is probably true that the geology at these two sites is unusually favorable for margin and crustal drilling, respectively. Penetration generally has been only a fraction of these record values. Nevertheless, even greater penetrations clearly are attainable by riserless drilling, and it is profitable to examine why they have not been achieved.

First of all it must be said that the targets of many holes are shallow and re-entry cones are not used. Commonly many shallow holes are preferred to a few deep ones. Where re-entry cones are deployed drilling may be terminated prematurely because of time limitations, technical failures, or bad weather. In these cases greater penetration might be achieved by re-entry on a subsequent leg. Sometimes, however, problems are encountered downhole (e.g., collapse of the hole, fractured rock, loose sand, heaving shales) which bring drilling to a halt. In this situation a change in the style of drilling, not necessarily requiring a riser pipe, must be adopted for greater penetration to be achieved, such as:

1. *Casing.* Casing can be set to stabilize the upper part of the hole. The present design of re-entry cone and hangers used by *Glomar Challenger* allows up to 3000 ft (914 meters) of 11¾ inch casing to be set. To date the maximum length of such casing set is 1741 ft (531 meters) in Hole 534A (Leg 76). The price paid for setting long lengths of casing is time. *Glomar Challenger* has a limited capacity for casing storage.
2. *Grout.* The hole can be grouted and re-drilled. Grouting is probably the only way to drill through fractured basalt. Again the price paid for using this technique is time.
3. *Mud.* The hole can be flushed with mud or even drilled with mud circulation without return if a sufficient volume of mud is available. *Glomar Challenger* can only spot mud, typically 50 barrels at a time, because of the very limited volume it can carry. The use of a mud tender, as adopted by the oil industry in the early days of offshore drilling and still in use, might be an effective way of extending *Glomar Challenger's* capability for sites drilled close to a port. *Glomar Explorer*, on the other hand, with tank space for 5200 barrels of liquid mud (Wetmore and McNary, 1977), could drill continuously with its own mud supply without return for a substantially longer period of time. Estimates of the amount of mud required for such drilling depend on the drilling experience of the person asked. Oil industry people, used to large annuli created in oil-well drilling (and in present *Glomar Challenger* practice), believe that the order of 50,000 barrels might be required for drilling 1000 meters without return, costing in the region of $750,000. Experience of shallow drilling without mud return (up to 300 meters of penetration in up to 200 meters of water depth) on the continental shelf of the United Kingdom, however, gave actual mud costs of about $100,000 per kilometer for a 5340-meter hole drilled in 1981.

Obviously, drilling without mud return in the deep ocean needs to be looked at in more detail, since the only experience is in shallow water. The pollution aspects of releasing large volumes of mud onto the ocean floor need to be studied before mud drilling without return is adopted. The use of oil-based drilling muds probably would be precluded.

4. *Heave compensation.* The lack of good heave compensation on *Glomar Challenger* has undoubtedly aggravated the problems of drilling. Improved heave compensation would benefit the stability of the hole and help maintain constant bit pressure and hence favor improved penetration. It is important to remember that the inadequacy of heave compensation in *Glomar Challenger* is not the fault of the compensator itself but is because it was introduced as an add-on unit to a derrick that is too short. Improved heave compensation has been proposed for *Glomar Challenger* (DSDP Program Review, 1981).

Adoption of the techniques outlined above might allow penetration of the ocean floor by drilling to reach 3000 meters. However, even with this penetration, riserless drilling alone would not be able to solve the problems of passive margin geology because on richly sedimented margins even deeper targets exist. Furthermore, safety consideration will inhibit the deep penetration of sedimentary sites without riser and full well control.

It is probably true to say that ocean crustal drilling has suffered most from the limited penetration achieved by *Glomar Challenger* to date. The source of the magnetic anomalies is unresolved, although drilling has brought home the fact that the magnetic structure is much more complex than the models. The dyke complex has only recently been demonstrated, and it is still not clear whether the ocean crust is like the ophiolites. Thus, ocean crustal drilling, uninhibited by safety considerations, probably has the most to gain from riserless drilling with increased penetration.

Core Recovery. Core recovery in *Glomar Challenger* drilling averaged 53% over the first 79 legs. It is generally better than this in homogeneous sedimentary columns but much worse, approximately 15%, in oceanic basement drilling. To some extent poor recovery can be compensated by downhole logging to fill in the gaps. Oil companies rely a great deal on drill cuttings and logging to determine stratigraphy. However, commonly they already have a general idea of the stratigraphy from other holes in the vicinity, some of which may have been cored. Furthermore, cuttings are not available in riserless ocean drilling. It is important, therefore, to adopt techniques which could improve the percentage of core recovery. Controlling the motion of the bottom hole assembly (BHA) is the essential requirement to achieve this. It has been shown that the motion of the BHA is much more complicated than simple rotation about its axis (Francis, 1981). The motion of the BHA can be made more stable by the use of better heave compensation on the drilling platform and by restriction of the pipe's freedom of movement in the top of the hole by installing casing.

The use of drilling mud also improves core recovery, probably because it damps out oscillations of the BHA more effectively than sea water and is more efficient in clearing cuttings out of the hole.

The extended core barrel (XCB), currently under development at DSDP, will receive its first test on Leg 86 in 1982. This is designed to improve recovery where hard and soft layers intercalate; e.g., in the Mesozoic chert areas of the West Pacific.

C. LOGGING AND DOWNHOLE EXPERIMENTS

For the first decade or so of its existence downhole logging has been the Cinderella of ocean drilling. The reasons for this have been manifold:

1. Logging, which usually is attempted only upon completion of a hole, nevertheless requires engineers and equipment to be on the ship for a complete leg. The cost of logging is, therefore, high compared to that from more accessible rigs. Logistic solutions to this problem have not been feasible with *Glomar Challenger*.
2. Logging through narrow-bore drill pipe (maximum tool diameter of 3⅞ inches) of holes whose diameter often considerably exceeds the usual diameter of the drill bit of 9⅞ inches has proved a technical challenge. In the early seventies the range of logging tools which could pass through the pipe was limited. Once clear of the pipe in the open hole, some tools have not coped well with the hole conditions. For example, standard sonic logs have often given poor results (Tixier, 1978).
3. Scientists interested in running their own downhole experiments have been unable or unwilling to participate on more than one or two legs, since only a few days are normally available for all downhole measurements in two months at sea.
4. Technical problems encountered in the drilling (e.g., collapse of the hole, failure of the bit-release mechanism) have resulted in logging not being attempted in many holes which have already yielded useful cores.
5. When time runs short, logging, being the last scientific operation in the hole, has inevitably been the first thing to go. Unfortunately some Co-Chief Scientists, partly through ignorance of the information that logging can provide, have preferred to drill additional holes rather than to log existing ones. Sometimes this has meant favoring quantity over quality.

The range of logging tools and downhole experiments which can usefully be deployed from *Glomar Challenger* is well summarized in the Report of the JOIDES Downhole Measurements Panel (1981) and need not be repeated here. Problems of quality control are discussed by Tixier (1978). The technical problems of logging from *Glomar Challenger* have now either been overcome or recognized so that time need not be wasted in running tools which give inadequate results. The organizational and logistic problems remain, but these might be partially relieved by scheduling logging minilegs. The JOIDES Downhole Measurements Panel Report discusses the advantages and disadvantages of such legs.

Before discussing major technological developments in the area of downhole measurements and logging, it is worth spending some time on the well seismic tool (Schlumberger, 1977), a commercially available system which has not been tried down *Glomar Challenger* drill holes.

Well Seismic Tool (WST). The WST provides depth calibration for seismic reflection records and is used frequently by the oil industry in offshore drill holes. Acoustic signals generated by an airgun at the surface are detected by a geophone anchored at successive depths in the hole. The resulting plot of transit time versus depth allows horizons identified seismically to be unequivocally associated with their equivalent downhole depth.

The location of seismic horizons in *Glomar Challenger* drill holes is not always straightforward, since the sonic log can never be operated over the total depth of the hole. Furthermore, sonic logs are often adversely affected by hole conditions.

The airgun equipment already on *Glomar Challenger*, together with that for the Oblique Seismic Experiment (OSE) (Stephen, 1979), could be used to run a WST type of log. Although the OSE has been run in a number of holes (on Legs 52, 65, 70), its objectives to date have been restricted to studying short-range propagation in the oceanic crust.

Safety Considerations. The restrictions imposed for safety reasons on deep-penetration, riserless drilling at the margins have already been touched upon. These restrictions might be eased if real-time monitoring of the presence of gas at the drill bit were available. Considerable efforts are currently underway in the oil industry to develop a device for sensing fluid (gas, water, etc.) entry at the bit. Coupled with measurement while drilling (MWD) telemetry, such a real-time monitoring device would make the riserless drilling of thick sedimentary sections considerably safer and allow deeper penetration to be contemplated.

Nor is it only riserless drilling which would benefit from MWD. In ocean-margin drilling with full well control (i.e., with riser and complete mud return) the application of MWD becomes a necessity. When using a long riser in deep water, the tolerance of mud pressure becomes so narrow and operating conditions so demanding that early detection of potential hazards is mandatory for operating safety. With long drill strings the delay in the return of mud and cuttings and in pressure surges makes prompt real-time detection of changes in conditions at the drill bit a necessity.

The significance of MWD to ocean drilling is explored further in the Section C. The application of MWD to riserless drilling would almost certainly require further engineering development of existing equipment in the oil industry.

Spudding-In on Bare Rock and Drilling in Hot Rock. The need to be able to spud-in on bare rock has been apparent for many years, in particular to allow the drilling of igneous basement which is too young to have appreciable sediment cover. A cement-filled drilling template has been proposed for use with *Glomar Challenger* (DSDP Program Review, 1981). Provided sufficient engineering support and time can be devoted to this development, there is no apparent reason why it should not be successful. However, the demand for engineering development and time is unlikely to cease with the first successful spud-in on bare rock. The fractured basalts and high temperatures likely to be encountered near the ridge axes will present additional problems. Drilling in the fractured basalt may require grouting and casing. The high temperatures encountered in hydrothermal systems or close to magma chambers could exceed the specifications of present drill bits and other downhole equipment.

Drilling the hottest parts of active hydrothermal systems (~350°C) should not be attempted without the use of mud and blow-out prevention and thus must await the arrival of riser drilling. Furthermore, it is important to note that the maximum temperatures to which mud and cement can be used are at present 315°C (600°F) for mud and 230°C (450°F) for cement.

These figures are unlikely to change much because there is no industrial demand for drilling to higher temperatures. The highest temperatures to which riserless drilling with sea water should be attempted into active hydrothermal systems will need careful appraisal by the Safety Panel.

Directional Drilling. Controlled directional drilling is a routine practice in the oil industry (for example, to allow many wells to be drilled from a single offshore platform) but has yet to be attempted in ocean drilling. Furthermore, there seems to have been little scientific demand for deviated holes up to the present. However, directional drilling could provide both scientific and economic benefits in ocean drilling:

1. Multiple holes could be drilled through the same re-entry cone; for example, to explore the heterogeneity of the oceanic crust. Considerable time could be saved by using a single re-entry cone.
2. The presence of sheeted dykes in the oceanic crust would be more easily explored with holes making an appreciable angle with the plane of the dykes.

Directional drilling technology has improved greatly from the early days of whipstocking, in which wedges were placed in the hole to deflect the pipe, and now relies on eccentrically coupled turbo-drills to effect the change of direction. Although extended reach drilling (ERD) is currently under development in the oil industry, which will allow hole deviations to build up at rates as high as 5°/100 feet (0.16°/meter) to angles as great as 80° from the vertical (Dellinger et. al., 1980), the special requirements of ERD make it unlikely to be applicable to ocean drilling this decade. Conventional directional drilling technology could however be used now. Deviation of the hole could not begin until the soft sediments had been penetrated and build rates of only about 5°/100 meters would be permissible. Deviations up to 60° from the vertical are technically feasible.

It is immediately obvious that hole deviation within a riserless drilling program would only be worthwhile if the following two conditions were satisfied:

1. Sufficient penetration must be available to allow an appreciable angle to the vertical to be developed. Assuming that deviation cannot begin until 200 meters below the sea bed, an angle of 40° will be developed at 1000 meters of penetration. If penetration of this order at any particular hole is unlikely to be achieved, there is little point in attempting directional drilling.
2. Sufficient time must be available to allow the deviation to be properly controlled. In particular, repeated downhole logging is required to record the azimuth and deviation from the vertical of the wellbore.

DARPA Seismometer. The successful installation of the 8-inch (20.3-cm) DARPA seismometer package in Hole 395A on Leg 78B, in addition to demonstrating the feasibility of emplacing large-diameter instrument packages, has important implications for earthquake seismology. The full "Marine Seismic System" will not be proved until 1982 or 1983, but the establishment of continuously recorded seismic observations on the ocean floor now seems likely. In the early sixties the World Wide Standardized Seismic Network (WWSSN) was installed, but it was never really worldwide because all the instruments were on land. Brief forays of seismic recording on the ocean floor have been made since then by ocean bottom seismographs, but their limitations have been too great to alter this general picture. The prospect of a truly worldwide, continuously recording seismic network is now in sight. Although funded by the United States Department of Defense, the scientific "spin-off" for earthquake seismology of a network of stations on the ocean floor is likely to be immense. The use of *Glomar Challenger* for installing these stations should be recognized as a scientific, as well as an economic, benefit.

Fly-In Re-Entry. The feasibility of lowering instruments into a drill hole without the use of the drill pipe is being explored (DSDP Program Review, 1981). Should this technique, also known as "wireline re-entry," be practicable from ordinary oceanographic ships, it could have important consequences both on the way downhole measurements are made and on the use of re-entry cones. These are discussed in more detail in the JOIDES Downhole Measurements Panel Report (1981). A first attempt at fly-in re-entry is planned for Leg 88.

Measurement While Drilling. Perhaps the most important development in downhole logging techniques in recent years is measurement while drilling

(MWD). Some half-dozen companies now offer MWD services to the oil industry. Sensors located in the bottom hole assembly (BHA) can measure such parameters as mud pressure, mud temperature, weight on bit, torque on bit, hole deviation, resistivity, and gamma ray. Four different telemetry systems have been developed for transmitting the information from the BHA to the drilling platform: (1) mud pulse, (2) hard wire, (3) acoustic, and (4) electromagnetic.

The role of MWD in improving drilling safety has already been discussed, as has its application to maintaining drilling efficiency in riser drilling. It could also be valuable for formation evaluation in riserless drilling, eventually even replacing the need for conventional logging. MWD has particular potential for ocean drilling for two reasons:

1. When drilling in oceanic depths a considerable amount of time is spent manipulating core barrels. This time would allow the transmission of fairly large amounts of downhole data, even at the low data rates of some MWD telemetry systems.
2. The chance of logging single-bit holes would be considerably improved.

If the full potential of MWD is to be realized, a considerable amount of engineering development would probably be necessary to make it compatible with riserless drilling. Existing MWD systems are not compatible with coring.

Downhole Sampling Tools. The hydraulic piston corer (HPC), in use since 1979, has provided *Glomar Challenger* with the ability to recover undisturbed cores from the unlithified sediment column and has received justified acclaim. A case can be made for developing other types of downpipe sampling tools:

1. *Hard Rock Drill* (HRD). This tool would be a rotary or rotary-percussive drill for drilling hard rock beyond the bit. The drill would be lowered down the pipe and locked into the BHA in the manner of a core barrel. The circulation pumps would provide the power for turning and hammering the drill, as well as for the necessary downward movement. The HRD would have a relatively thin-walled, high-strength drill stem and either a tungsten-carbide or diamond-studded kerf. One objective of the HRD would be to cut a clear and complete core in hard rock. Another, perhaps more important, objective results from the clean hole beyond the bit, which provides an excellent place to sample pore fluids and do flow tests using a small wireline packer. A third use for the HRD might be for overcoring-type stress measurements. The HRD might also be useful in hard or chertified sediments.

A piggy-back drill similar in concept to the HRD is already in use in shallow boreholes (up to 300 meters of penetration in up to 200 meters of water depth) on the continental shelf of the United Kingdom (D.A. Ardus, personal commun.). In this case a drill rod of narrow bore is used inside drill pipe of narrow diameter, so that the latter acts as a riser. This approach could probably not be scaled up to oceanic depths (i.e. a slimline riser is not being proposed), but the technique is obviously relevant to the development of an HRD.

2. *Downhole Vibracorer* (DHVC). Recent experience has shown that the HPC is a poor tool for sampling terrigenous deposits. A DHVC might be the best way to sample sandy and highly friable semi-consolidated sediments. If successful it would greatly extend the depth to which a complete and oriented sedimentary core could be obtained.

3. *Hydrogeological Sampling Tool*. This tool would incorporate a downhole pump capable of pumping fluid in and out of a packed off interval. Control would be exercised by downhole chemical analyzers which would tell the tool when to sample and when to flush. The objective would be to obtain uncontaminated samples of crustal pore water.

4. *High-Temperature Logging Tools*. The upper-temperature limit for most commercial logging tools is 350°F (180°C). However, a range of hostile environment logging tools are available which can operate to temperatures of 500°F (260°C). These temperature limits match the capabilities of logging cables. Ordinary logging cable can be used up to 180°C. Above that Teflon insulated cable is available for use up to 260°C. The only parameter to have been logged above 260°C is temperature itself, to about 320°C by Sandia Laboratories.

If the need arose to log drill holes in the ocean floor to temperatures above 260°C, special cables would be required in addition to the development of the tools themselves.

D. RELATED GEOPHYSICAL AND GEOLOGICAL STUDIES

Organization of Site Surveys. The range of instrumentation which can be deployed for site-survey work is wide and sophisticated: multichannel seismic reflection profiling, SEABEAM, GLORIA, submersibles, and Deep Tow, to name a few. The cost and variety of ocean drilling is such that full use should be made of all these techniques, where relevant, in the definition of sites to drill. For this to be possible the general area of drilling sites must be known far enough in advance for these techniques to be programmed. In addition time must be available for the site surveys to be interpreted and digested before drilling commences. Only then can the site-survey information make its proper impact upon the choice of drill sites.

The experience of the past few years with *Glomar Challenger* has been very disappointing in this respect. The advance notice of the program on *Glomar Challenger* has been insufficient for either GLORIA or SEABEAM operations to be scheduled in advance of drilling. Site surveys arranged through the JOIDES machinery have had insufficient lead time over the actual drilling. To make matters worse there has even been a lack of interaction between people evaluating the site surveys and those involved in the actual drilling. These organizational deficiencies have to a large extent derived from the 2-year time frame of the program on *Glomar Challenger*. A 5-year time frame would allow better advanced planning and at the same time allow more flexibility into the program. We recommend, therefore, that the following schedule should be adopted within the overall framework of a 5-year drilling program:

D-3 yr General area and objectives of drilling

	leg specified. Evaluation of existing data set. Recommendation for preliminary site survey by appropriate panel.
D-2 yr	Preliminary Site survey completed. Co-Chief Scientists appointed. Preliminary selection of sites. Contact with Safety Panel to define safety requirements.
D-2 yr to D-1 yr	SEABEAM survey. GLORIA survey (where relevant). Multichannel seismic reflection profiling (where relevant).
D-1 yr	Submersible survey (where relevant). Deep Tow survey (where relevant). Safety Panel preview. Scientific staff selected.
D-6 mths	Completion of site survey interpretation. Drill sites selected. Final Safety Panel review.
D	Drilling leg begins.

The adoption of a schedule such as this would have considerable advantages over the present system:

1. Time is available for surveys to be carried out in the proper sequence and to be interpreted.
2. The early appointment of Co-Chief Scientists allows them to take an active part in the interpretation of the whole range of site-survey activity and thus to become thoroughly familiar with the complete data set prior to drilling. Individuals who are not prepared to participate in this activity are not suitable candidates for the position of Co-Chief Scientist. Indeed it is important that Co-Chief Scientists have sufficient breadth of interest for the job and are not "blinkered" experts interested only in their narrow speciality.
3. Early selection of the scientific staff similarly allows them to prepare themselves adequately for the forthcoming drilling. It is appropriate that the scientific staff include at least one of the geologists/geophysicists involved in site-survey interpretation.
4. Finally, the more extended time frame of site surveys would allow time for the re-direction of drilling objectives as the results of these surveys emerged.

SEABEAM. Just as a field geologist would not think of going into the field without a good topographic map, so drill sites in the ocean floor should not be chosen without the availability of such a map. SEABEAM is the best available tool for producing detailed bathymetric maps and, since this equipment is now being installed in more ships (installation is planned for the Scripps vessel *Thomas Washington* and the German ship *Sonne* in the near future), a SEABEAM survey should be a routine part of the process of site selection.

The value of a SEABEAM survey is particularly great in areas of topography such as encountered in drilling active margins and ocean crust. The recent post-drilling SEABEAM survey of the Leg 78A sites on the Barbados Ridge was particularly impressive. Had this survey been available before the leg, the choice of sites would probably have been different.

Long Range Side-Scan Systems. The long-range side-scan sonar systems are complementary to the SEABEAM system. GLORIA for example cannot produce a bathymetric map but, with an ability to insonify up to 1000 km^2 of sea bed per hour, it can very rapidly produce a picture of the morphology of a whole region. It has proved particularly suitable for mapping the tectonic fabric of the oceanic basement, sedimentary bed forms and large scale sedimentary features such as slumps and slides. Because only one GLORIA exists at the present time, operated by the United Kingdom Institute of Oceanographic Sciences, it would be impracticable to recommend that GLORIA be used for all site surveys. Nevertheless, site selection would undoubtedly be improved by the availability of GLORIA data.

The value of GLORIA data was demonstrated recently in a post-drilling survey of the Costa Rica Rift, covering sites 501, 504, and 506 (Searle, 1981). This survey demonstrated particularly well the marked contrast between site 505, where many fault scarps are exposed, and sites 501 and 504, where the basement is almost completely buried.

Seismic Reflection Techniques. A wide range of seismic reflection techniques have been deployed for site-survey work in the past, from 3.5 kHz profiling, single-channel seismic reflection profiling with airgun to multichannel seismic profiling. The depth of penetration, resolution and velocity information provided by these various systems vary widely. Ideally a reflection survey in the vicinity of a drill site would give continuous, detailed measurements of velocity so that the depth of reflection events could be accurately determined. The apertures of commercially available multichannel arrays are still too small to provide accurate array velocities, and hence reliable interval velocities, in oceanic depths.

The lack of good interval velocities from seismic surveys in oceanic depths emphasizes the need for velocity measurement on core samples and on downhole logging (WST and long spacing sonic logs) to ensure that reflection times are properly converted to depths.

Wider aperture arrays can be created synthetically by common-depth-point seismic profiling conducted by two or even three ships. By proper spacing of the receiving arrays and control of the shot pattern synthetic apertures ranging from 10 km to 25 km can be produced allowing 96-fold to about 226-fold data. Such multi-ship synthetic aperture measurements will be important in determining deeper crustal structure and will become essential when very deep-penetration drilling in oceanic depths is envisaged.

But the most pressing need in seismic reflection technology for the program of ocean drilling is to provide a system of profiling capable of matching in depth of penetration and resolution the hydraulic piston corer (HPC). Before the advent of the HPC the unlithified sediments were so disturbed by drilling that the coarse resolution of airgun seismic systems operating from the sea surface was adequate. The success of the HPC has allowed stratigraphy to be studied on a centimetric scale. The problem now is to choose the best palaeoenvironmental sites for the HPC to sample. This requires a profiling system with a penetration of approximately 200 meters and a resolution of approximately 0.5 meters. Such resolution is impossible with systems operating from the sea surface but is achievable in near-bottom profilers operating at frequencies of a few kHz. A number of oceanographic laboratories have such systems either in use or under development.

Submersibles. Submersibles have a role to play which is likely to increase in the second half of the eighties. At present the United States submersible 'Alvin' is restricted to depths less than 4000 meters. In 1983 the French submersible SM-97 (able to reach 97% of the ocean floor) will become available with a 6000-meter capability.

Submersibles are most valuable in areas of rugged topography. Power and buoyancy limitations restrict their sampling ability. Because of their limited range it is essential that they land in the right place so a necessary pre-requisite to their operation is a good bathymetric map (i.e., SEABEAM). In spite of these constraints, two roles can be envisaged for submersible operations:

1. In conjunction with drilling on the axis of a mid-ocean ridge, the submersible can provide a detailed map of the surroundings — the distribution of fissures, fault scarps, etc. It might even be possible for a submersible to construct a spud-in frame for drilling bare rock. Certainly the submersible will be required to locate the best site for such drilling.
2. In a number of places on the sea floor, substantial sections of the sedimentary column are exposed in major submarine escarpments; e.g., the Blake Escarpment of the US eastern seaboard and the Malta Escarpment in the Mediterranean. Sampling of such escarpments by submersible could obviate the need for drilling some margin sites, especially if sufficient seismic coverage is available to trace horizons to outcrop.

Sampling in Site Surveys. The role of submersibles in sampling horizons which outcrop on steep scarps has just been mentioned. Occasionally, horizons identified seismically can be traced to outcrops in more subdued terrain and are accessible to sampling by piston corer (penetration $\leq$15m below sea bed) and/or by dredging. Such opportunities of providing ground truth to aid the interpretation of seismic surveys prior to drilling must not be missed. The more extended time frame proposed for site surveys makes this a practical proposition.

Associated Land Geology. Much of land geology is marine geology and we should not lose sight of the guidance that land geology can give to understanding the results of drilling. The imbricate structures found on active margins exist on land, ophiolites are found above sea level and the tilted blocks of passive margins are also visible on land.

Geologists selected for the shipboard staff should be familiar with the sub-aerial homologues of the rocks they are likely to encounter on a drilling leg. The earlier appointment of scientific staff would allow those not so well equipped to prepare themselves for a drilling leg by suitable field trips on land.

E. CONCLUSIONS AND RECOMMENDATIONS

1. Scientific ocean drilling prior to 1990 will be riserless.
2. Although individuals have their own preferences for the most suitable drilling platform in the next few years, scientific ocean drilling was seen by the whole COSOD meeting as a long-term endeavor stretching well beyond 1990. On this basis and because of its growth potential, *Glomar Explorer* is the preferred drilling platform. The continuation of an internationally funded drilling program is also a factor which bears on the choice of platform.
3. The international collaboration established by the IPOD program has been extremely fruitful and must not be abandoned.
4. Similarly the expertise developed by the Deep-Sea Drilling Project must be retained.
5. Considerable potential remains to be exploited in riserless drilling provided sufficient resources of engineering development and of time are available.
6. The number of items requiring engineering development is considerable — hard-rock base plate, adaptation of MWD technology to riserless drilling, downpipe sampling tools, and fly-in re-entry, to name but a few. As organized at present it is unlikely that the engineering group at DSDP can bring these developments to fruition soon enough for them to be exploited fully in the late eighties (a reflection on their numbers and budget, not on their competence). We recommend increased support for engineering development, with funding separate from the operational requirements of the ship.
7. The present program on *Glomar Challenger* suffers acutely from last minute arrangements and hurried preparation. This indecent haste should be avoided. The time frame of leg planning must be extended to a minimum of three years. This would allow time for the full range of sophisticated site-survey techniques to be deployed and for the results to be interpreted before drilling commenced. Similarly the earlier appointment of both Co-Chief Scientists and the scientific staff would allow them to prepare themselves better for their tasks. Early discussions with the people in charge of drilling operations would also be possible, something which should not be left until the drilling leg actually starts.
8. The extended time frame must not be rigid. As much flexibility as possible must be built into the system to allow for time overruns on difficult, new drilling objectives such as drilling hard rock. Occasionally it will be desirable to return to re-entry holes which were abandoned before the drilling objectives were reached.

F. REFERENCES

Deep Sea Drilling Project Program Review for the National Science Foundation, 29 June 1981.

Dellinger, T.B., Gravley, W., and Tolle, G.C., 1980, Directional technology will extend drilling reach, Oil and Gas Journal, v. 78, p. 153-169.

Francis, T.J.G., 1981, Effect of drill string movement on the shape of the hole and of the cored rocks at Hole 459B, *in* Hussong, D.M., Uyeda, S., et al., eds., Initial reports of the Deep Sea Drilling Project, Vol. 60: Washington, D.C., U.S. Gov't. Printing Office, p. 835-840.

JOIDES Downhole Measurements Panel, June 1981, Downhole measurements and experiments in deep sea drill holes.

Parkinson, S.T., and Saren, M.A., 1981, Offshore technology: A forecast and review, Financial Times Business Information Ltd.

Schlumberger, 1977, Services Catalog.

Searle, R.C., 1981, GLORIA survey over Costa Rica Rift Sites 501, 504, 505, *in* Cann, J.R., Langseth, M.G., eds., Initial reports of the Deep Sea Drilling Project, Vol. 69: Washington, D.C., U.S. Gov't. Printing Office (in press).

Stephen, R.A., 1979, The Oblique Seismic Experiment in oceanic crust — Equipment and Technique Marine Geophysical Researches, v. 4, p. 213-226.

Tixier, M.P., 1978, Quality control and procedure for processing logs of Legs 46, 48, 50, 51, 57, 60, 61: Report for Deep Sea Drilling Project.

Wetmore, S.B., and McNary, J.F., 1977, The *Glomar Explorer* as a deep ocean drilling and coring ship: Report prepared for Deep Sea Drilling Project by Global Marine, Inc.