WHITE PAPER
JOIDES OCEAN HISTORY PANEL
DRAFT 4-13-94

EXECUTIVE SUMMARY

The Ocean History Panel outlines four global experiments in forcing and response of global environmental change, with recommendations for implementation in the near term (1994-1998), medium term (1998-2003) and long term (post 2003). These experiments, which evolve from and update COSOD-II themes, seek to understand the evolution, sensitivity, and response of the global environmental system to: (1) orbital forcing; (2) internal feedbacks and rapid environmental changes; (3) tectonic, volcanic, and extraterrestrial forcing; and (4) global sea level changes. Each experiment requires a spatial array of sites, which samples appropriate latitudinal, depth, and age ranges. For the near and intermediate term implementation, we anticipate modest technological change, including enhanced recovery with APC, XCB, and rotary coring systems, increased resolution and variety of down-hole logs and shipboard measures of sediment composition with non-intrusive sensors, better access to shallow water drill sites, and improved core-log integration. In the long term, the OHP goals require 100% complete recovery of all lithologies, and the ability to sample for a larger suite of measurements at high resolution. This would be facilitated by 1) a change to 5 inch drill pipe to provide larger-volume samples, 2) Successful implementation diamond coring or equivalent systems, 3) access to jack-up rigs for shallow water drilling, and 4) improved heave compensation for ultra-high resolution logging. To support the development of suitable well-posed experiments in scientific ocean drilling, OHP sees a critical need for timely site surveys of potential sites, earlier in the evaluation of drilling proposals than occurs at present.

WHITE PAPER
JOIDES OCEAN HISTORY PANEL
DRAFT 4-13-94

I. INTRODUCTION

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

Previous strategic plans for studies of ocean history, resulting from COSOD-II in 1987, the Sediments and Ocean History Panel (SOHP) White Paper in 1989), and the ODP Long Range Plan (REF) were developed under four temporal and process-oriented themes: Neogene paleoceanography, pre-Neogene paleoceanography, carbon cycle and productivity, and sea level (JOIDES Journal 15(1):40-58, 1989). Progress on these themes opens a new opportunity, to define a set of four interconnected **global experiments** to test hypotheses and refine understanding of the forcing and response of large-scale environmental change. The experimental strategy defined here updates and implements the paleoenvironmental goals of COSOD-II, which remains a strong community vision (*Imbrie et al., 1987, Scientific Goals of an Ocean Drilling Program Designed to Investigate Changes in the Global Environment, Report of the Second Conference on Scientific Ocean Drilling (COSOD-II), ESF, Strassbourg, 15-46*). We seek to understand the evolution, sensitivity, and response of the global environmental system to: (1) orbital forcing; (2) internal feedbacks and rapid environmental changes; (3) tectonic, volcanic, and extraterrestrial forcing; and (4) global sea level changes.

In the following sections, we first outline our experimental view of the global environmental system. Then, for each global experiment, we describe the scientific justification, the overall objectives, the current state of the art based on prior drilling, and an implementation strategy for the short term (1994-1998), and medium term (1999-2003) of ODP, and for a New Era of Ocean Drilling (post-2003). Following description of each experiment, we summarize the common programmatic priorities, and outline the evolution of technology needed to accomplish our long-range vision.

II. A Global System View

In the context of OHP interests, the climate system (Fig. 1) is considered to include the entire hydrosphere, atmosphere, cryosphere, biosphere, and land surface. Given information about the **forcing** of the climate system (the tectonic and orbital inputs that are external to the system), and the **response** of the system (the climatic record), drilling strategies can be developed "to identify and understand the coupled physical, chemical and biological **mechanisms** that are the immediate causes of each observed change in climate (COSOD II, 1987)." To decipher the mechanisms of environmental change, we must first consider the nature of the forcing and response. The climate system is a complex mixture of forcing on many time-scales and responses of many types and rates. In the context of the fluid earth (atmosphere, hydrosphere, cryosphere), **EXTERNAL** forcing includes both the pattern of solar energy input, and the tectonic processes, such as change in the shape of continents and ocean basins, the orography of continents, large scale volcanism, and meteorite impact. **INTERNAL** forcing describes the effect of one climate component on another, even though in some cases the internal forcing is a direct or indirect response to external forcing. For example, atmospheric CO2 levels force global temperature but are responses to tectonic, volcanic, and other forcing. Climate system components can be forced **DIRECTLY** or **INDIRECTLY** and exhibit responses that are **LINEAR** or **NONLINEAR**.

External forcing can be **PERIODIC**, such as orbitally-induced changes in solar radiation, an **IMPULSE FUNCTION** such as a meteorite impact or CO_2 emissions from a Large Igneous Province, or a **STEP FUNCTION** caused by the opening of a critical gateway or rapid surface uplift of mountains and plateaus. Given this wide range of external forcing and the complexity of the climate system, it is no surprise that some of the largest and most interesting climate responses are **FEEDBACK PROCESSES** within the system. For example, the El Nino variations are nonlinear feedback responses to changes in the directly forced annual cycle of the Pacific. Similarly, the 100-Ky cycle of the Late Pleistocene is not directly forced but reflects amplification of directly forced cycles or oscillations embedded within the natural climate system. The history of the Earth's environment is exceedingly complex and only by constructing experiments using our knowledge about specific external forcing and climate system history can we identify and understand the role of more complex indirect and feedback processes in the evolution of our present environment. In short, our goal is to quantify the feedback processes that bring about large-scale environmental change.

How do these concepts apply to the design of drilling strategies to understand the causes of environmental change in earth history? We hypothesize that environmental changes fall into three distinct categories. The **TECTONIC** forcing includes the trends, impulses, and steps in response to tectonic processes. These features represent major changes in the climatic **mode** that are associated with major differences in thermal regimes, in the global pattern of winds, and in the chemical mass balances and three-dimensional patterns of ocean circulation. Superposed on these tectonic patterns is the **ORBITAL** forcing characterized by periodic oscillations on timescales of 20-400 ka, and responses that reflect both direct and indirect forcing. Finally, **INTERNAL** forcing, the interaction of feedback processes that create climate oscillations in the absence of any direct external forcing, are illustrated in sub-orbital (<20Ka) climate signals.

In all three of these categories, our experimental goal is to assess the **sensitivity** of the climate system, and to "formulate and test quantitative models of the mechanisms of climate change" This concept of forcing and response forms the experimental framework for constructing drilling strategies to understand the changes in the Earth's environment. A well-posed series of experiments will target different specific components of the climate system on a variety of timescales. Below, we describe the drilling strategies for four experimental themes, the orbital, internal feedback, tectonic-volcanic-impact, and sea-level forcing of the Earth's environment.

III. EVOLUTION AND SENSITIVITY OF GLOBAL ENVIRONMENTS: FORCING AND RESPONSE EXPERIMENTS:

OHP Experiment 1: Orbital forcing, Climate Response.

Scientific Justification

ODP-based records of biotic, geochemical, and sedimentological changes in past oceans provide compelling evidence that the Earth's climate and oceans have varied in response to changes in orbital geometry (the Milankovitch effect) over all time intervals (from Holocene to Cretaceous). This orbital variation, which affects how Earth collects solar energy, changes systematically with periods of 23 Ky, 41 Ky, 100 Ky, 400 Ky, and 2 Ma. This provides a specific temporal and spatial forcing on the ocean-climate system. These changes provide a framework to construct geophysical experiments to test hypotheses concerning the natural causes of climate change. Examples of such hypotheses and questions include:

Do changes in solar radiation force changes in ocean chemistry and atmospheric pCO_2? The high coherence between many paleochemical indices (such as carbon isotopes, Cd/Ca and Ba/Ca in foraminifera) and biogenic fluxes with both orbital variations and the trapped CO_2 in the Antarctic ice sheet indicates that the controls atmospheric CO_2 at orbital time scales. However, the mechanisms of this control and the feedbacks remain unclear.

What is the sensitivity of the ocean-climate system to known changes in external solar radiation forcing and how important are internal feedbacks? ODP studies have shown that many components of the ocean and climate system respond to periodic changes in the seasonal distribution of solar radiation caused by changes in the Earth's orbit. These climate responses provide the opportunity to understand the sensitivity (i.e., the gain function) of various processes and areas, and to help unravel the importance of direct forcing versus internal feedbacks in global environmental changes.

Can direct forcing cause rapid changes in the ocean-climate system? Recent results from both Quaternary and ancient sediments indicate significant abrupt changes in ocean temperatures, faunas, and isotopic composition on time scales as short as a few tens of years. This suggests that the climate system contains thresholds, which if crossed by orbital or other forcing may push global environments into new modes of operation. Understanding the history, process, and dynamics of these thresholds has direct relevance to questions of current and future global change.

Objectives

This experiment seeks to test the response of the ocean-climate-biosphere system to changes in the seasonal distribution of radiation caused by variations in the Earth's orbit. Specifically, OHP's objective is to measure the response of the ocean to this known forcing, including ocean circulation, ocean chemistry, and biology. OHP promotes the integration of these records of paleoceanographic variability with numerical simulations of past conditions to evaluate quantitatively the sensitivity, variability, and evolution of global change processes.

Changes in Earth's orbit are known in detail for the past 10 Ma, and in general for much longer time spans. The ability to identify a specific external forcing on the earth-ocean climate system provides the opportunity to make a suite of unique global geophysical experiments. Responses of the climate-ocean system can be measured and compared to the forcing to identify both the linear responses, which should follow naturally from changes in orbital forcing, and poorly-understood internal feedbacks (which include pCO_2) and perhaps internal oscillations within the global system. Understanding both externally and internally forced changes is necessary in order to fully constrain the mechanisms and sensitivity of environmental change. This experimental strategy requires the generation and analysis of high resolution data on the ocean's response under different combinations of external orbital forcing, and different sets of surface boundary conditions.

The periodicities of the orbital forcing define the temporal resolution that studies need to address the response oceanic and climatic systems. For example, sampling intervals of about 4 Ky. (i.e., 8-cm sampling in sediments accumulating at 20 m/my) are needed to resolve the ocean responses related to precessional of the equinoxes at 19-ky and 23-ky rhythms. Experiments designed to test forcing-response hypotheses will thus require high quality stratigraphic-chronologic frameworks, including oxygen isotope stratigraphy, GRAPE density measurements, magnetic susceptibility, video imaging, reflectance spectroscopy, and down-hole logging.

Because the ocean has strong regional and temporal differences in its circulation and properties, these experiments need to develop **global three-dimensional arrays** of paleo-ocean properties. These spatial arrays of drill sites need to have enough geographic and vertical resolution to identify key water masses, circulation patterns, biotic, thermal, and chemical gradients.

OHP envisions a series of orbital experiments under different sets of Earth-system boundary conditions (for example, an Earth with and without major polar ice sheets, higher and lower concentrations of CO_2, different continental locations and mountain elevations). This strategy will help to isolate the role of each boundary condition in the feedbacks which sensitize global environments to change. Thus, the orbital experiment will be carried out in selected intervals throughout the geologic record. Because core recovery, stratigraphy, and chronology is best in younger sediments, many of these tests will be carried out in Neogene sediments. Examination of sensitivity to boundary conditions, however, dictates orbital experiments in Paleogene and Cretaceous sediments as well, where key boundary conditions, such as atmospheric pCO_2, deep ocean circulation and chemistry, and continental positions and elevations, were radically different than in Earth's recent past.

State of the Art

As a result of ODP drilling, we have significantly extended our understanding of orbital climate signals in the Neogene. Using the orbital changes as a pacemaker has resulted in an orbitally-tuned timescale back to the Miocene/Pliocene boundary. With continued work these timescales will likely extend into the Miocene and beyond. Orbitally-tuned timescales are possible because of the development non-intrusive sensing techniques (e.g., GRAPE, magnetic susceptibility, video imaging, and reflectance spectroscopy) and software that permit the construction of complete and continuous composite depth sections in APC/XCB cores. The recognition of orbital cycles in deep-sea sequences has resulted in time resolution that was never thought possible for the pre-Pleistocene. Orbital timescales have provided a precise chronologic framework that can be used to measure rates of geologic and evolutionary processes.

We now know that orbital-scale cycles are pervasive in the sedimentary record. The amplitude and timing of the cycles vary spatially within the oceans and evolve through time. For example, initiation of rhythmic variations in monsoon upwelling in the Arabian Sea associated with Himalayan uplift 7 million years ago isolates the sensitivity of the Asian monsoon's response to continental isolation. As the patterns of orbital response emerge with increasing spatial and temporal resolution, they will provide are major constraints and implications for mechanisms of climate change.

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

Near-term Implementation (1994-1998)

Although it is possible that new proposals may be submitted that are mature enough for early drilling, it is likely that proposals currently scheduled or highly ranked by OHP will define most of the field programs of the next four years relevant to the orbital change experiment. For the purposes of this experiment OHP expects that the following field programs may be completed between 1994 and 1998:

1) Drilling a high-resolution depth transect in the western equatorial Atlantic to address climatic and oceanographic variations in this critical area of cross-equatorial transport of surface and deep waters, and to examine climatic history of South America (Leg 154, 1994).

2) Drilling in the Mediterranean to understand the origin, significance, and geochemistry of Plio-Pleistocene sapropels and address questions about the influence of rhythmic Late Cenozoic global circulation and climate changes on organic carbon deposition.

3) Refining the role of orbital forcing in the climate evolution of high latitude and polar oceans. Current OHP focus is on the second leg the Neogene history of the Arctic and high latitude North Atlantic (NAAG-II), a region important in deep water formation and a possible trigger for global climate changes. Additional drilling in the Caribbean will help constrain Neogene history of mid-depth waters of the North Atlantic.

4) Use of climatically sensitive upwelling areas as monitors of global change, to establish marine-terrestrial linkages and estimate the contributions of upwelling productivity to geochemical budgets. Drilling in the near future will focus on the Cariaco Trench, the California Margin and the Benguela Current/Namibia upwelling systems to recover long histories from these high-sedimentation-rate areas. Studies will concentrate on their response to orbitally-induced high latitude cooling and changing wind systems, the evolution of these upwelling systems, and their changing role in long-term carbon storage. The high sedimentation rates and laminated sediments in some locations will give ultra-high resolution records for the late Neogene as well.

5) Assessment of southern hemisphere climates and patterns of global deep water circulation in the South Atlantic and in the South Pacific.

Over the next four years we look for technological advances that will improve core recovery with existing APC and XCB systems. For example the recent innovative use of washover techniques to extend continuous APC recover should be pursued. Advancement of shipboard measurement and analysis techniques are critical for and reliable construction of complete composite depth sections and for core-log integration. We expect rapid advances in the variety and efficacy of non-intrusive sensing techniques, which will provide rapid, high-resolution measures of sediment properties.

Medium-term Implementation (1998-2003)

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

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

Potential drilling programs in these areas could include a high resolution bathymetric transect in carbonate sediments in the sub-Antarctic Atlantic sector filling gaps in Southern Ocean history revealed by previous drilling, a bathymetric transect in the western North Atlantic to give open ocean sites with resolution comparable to that of ice core records for addressing the changes in circulation and heat and carbon budgets on these time scales, a high-resolution Neogene drilling in the eastern equatorial Atlantic to address cross-equatorial heat transport, productivity, and the history of intermediate and deep water circulation; and programs to focus on the deep and intermediate water history in the southeast Pacific, the role of the Bering Sea in glacial/interglacial climate change, and North Atlantic variations in proximity to the Laurentide Ice sheet.

A key feature of a number of these programs is to extend the astronomically-tuned timescales into Miocene and beyond. This new application of the orbital response strategy probably has the best potential for determining the high-resolution age models needed to make meaningful estimates of the rates and fluxes of climate-sensitive sediment components. These data are necessary to reconstruct accurately the response patterns of past oceans when many important boundary conditions were different. Comparison of Quaternary and Neogene responses at high resolution is a critical part of the strategy for understanding the sensitivity of the ocean-climate system. In addition, by 2003 we expect to see the beginnings of orbital experiments in older (Paleogene and Cretacous) sediments, based on progress on lower-resolution studies of these materials in the near future.

In the medium term we expect continued evolution of measurement techniques. Development of additional non-intrusive sensors will facilitate more widespread high resolution studies, but addition of new geologic and geochemical proxies will put great demands on sediment sampling. We expect greater need for multiple coring at each site.

New Era of Scientific Ocean Drilling - Post 2003

As we look forward to a new era of ocean drilling with enhanced capabilities, the role of orbital forcing of the oceans and the global environment will remain a first order priority. As such, the continued emphasis on the 100% complete and continuous recovery of all lithologies will be the highest operational priority of OHP. We envision that the enhanced coring/recovery capabilities will enable OHP to address questions of orbital forcing in more dynamic and high risk environments such as in high accumulation-rate continental margin, shallow water, and polar ocean sites. We expect the need for geographically distributed sites to continue. The growth in the variety of geologic proxies and the need for high-resolution sampling suggests a change to larger core diameters, perhaps using 5-inch drill pipe. This change would facilitate development of higher-resolution logging tools, which is critical for assembly of complete stratigraphic sections beyond the reach of APC cores.

Another high priority will be to improve recovery continuous and high quality older Neogene and Paleogene sediments so that orbital-scale variations in biotic, chemical, and sediment components can be quantified under different sets on Earth boundary conditions. These different Earth modes will test the response models developed in the more recent geologic record and should provide important insights to the role and sensitivity of the ocean to orbital forcing.

OHP Experiment 2: Rapid Environmental Changes and Internal Feedbacks.

Scientific justification

Analyses of ice cores and rapidly-accumulating oceanic sediments demonstrate that rapid environmental changes, on the century-to-millennial scale, are common in Earth's recent history. These rapid changes, in the absence of obvious external forcing, pose critical questions: 1) Is Earth's environmental system inherently stable, or unstable? 2) If perturbed by external forcing, would the earth return to its initial, unperturbed state, or might it seek a new state? 3) Do feedbacks in the earth-atmosphere-ocean-ice biosphere system produce predictable oscillations, or are some aspects of global environmental change unpredictable?

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

Objectives

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

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

State of the art

Dramatic changes in the ocean have recently been found in North Atlantic sediments, especially during the last glacial cycle. These changes, referred to as "Heinrich Events" suggest massive changes in both upper-ocean and deep-sea environments, as well as in atmospheric circulation and chemistry, with potentially global consequences. The cause is uncertain. One hypothesis is that ice surges from unstable North American ice sheets are responsible and that the resulting influxes of fresh water modify thermohaline circulation. If this is the true, then these effects may not be important in future, warmer, climates. Another hypothesis consistent with recent findings of rapid interglaical climate oscillations in Greenland ice cores, suggests that changing distributions of salt in the oceans via coupling of atmospheric and oceanic circulation may induce thermohaline oscillations independent of ice sheets. If so, the future of climate is uncertain. Whether these rapid climate changes are global or regional, whether they occur at all times or only in certain climatic states, if they are unique, or among a large array of rapid climatic phenomena, remains unclear. Details of the current hypotheses and their global implications remain to be tested.

Near-term implementation (1994-1998)

Proposals now in the ODP advisory structure begin to address rapid climate changes. Some potential targets for the next four years exist in North Atlantic sediment drifts (scheduled for drilling in 1995), the Blake-Bahamas Outer Rise, the Southern Oceans, and selected basins on continental margins such as the Cariaco Trench, the California Borderland basins, and Southwest Africa. Because suitable drilling targets do not exist everywhere, recovery of these types of records does not always requires a full drilling leg. Incorporating this type of site into geographically appropriate (but not necessarily thematically related) drilling programs will require scheduling flexibility and foresight.

To maximize the scientific return from a finite collection of sediments, we expect technological developments in "remote" sensing techniques that can provide information on chemical, mineralogical, or physical properties at high resolution while preserving material for other analyses that consume the sediment. We also look for drilling technology that improves core recovery, especially for such lithologies as diatomaceous ooze and alternating soft/hard sediments and in gassy organic-rich sediments that expand on retrieval. To apply the full range of multi-parameter techniques necessary for high-resolution studies will require significant revision of sampling and curatorial protocols.

Medium-term implementation (1998-2003)

In the medium term, we expect additional high-quality sites to be identified that will yield a first look at global distributions of rapid climatic events. Moderate improvements in coring capabilities are likely, using existing drilling technology. We anticipate new geochemical and biotic proxies on small samples and better automation of existing proxies. This will better characterize environmental changes at high temporal resolution, but will also put greater demands on sediment sampling. To accommodate this demand, we expect the need for multiple-holes to be drilled at selected sites. To utilize sediment from multiple holes fully requires precise correlation between holes, but advances in computing and data storage, and improvements in high-resolution scanning techniques, will respond to this need.

New Era of Scientific Ocean Drilling - post 2003

Predicting the long-term development of a field that is just now being defined is risky, and must be very general. We predict the need to study rapid environmental changes under climatic boundary conditions warmer than those of today or the late Pleistocene ice ages, as a test of possible future scenarios for Earth's climate system. Technological advances may dictate return to previously drilled sites to improve or extend records that receive preliminary study in the next 10 years and pose new questions. We expect the needs for high-resolution sampling to grow, and this will put great demands on sediment cores. One solution could be a change to larger diameter cores (5-inch drill pipe) which will supply more sediment in better condition for high-resolution sampling and reduce (but not eliminate) the need for drilling multiple holes at each site. Shallow water, organic-rich sediments are compromised by gas expansion, and may require special drilling techniques to optimize recovery. Addition of alternate drilling systems, including jack-up rigs for shallow water drilling, or diamond coring systems, would facilitate recovery of long records from corals, which could yield information on seasonal-to-interannual climate variations in the distant past. We look for ultra-high resolution logging tools and improvement in ship heave compensation to provide down-hole information to place cores into a true depth framework.

OHP Experiment 3: Tectonic, Volcanic, Biotic, and Extraterrestrial Forcing.

Scientific Justification

Long-term changes in global climate respond to tectonism and volcanism via their influences on the carbon cycle, Earth's albedo, and energy balance (ocean and atmosphere circulation). Over much of the past 120 Ma, Earth's climate has been warmer than present, particularly at higher latitudes. This climatic difference is attributed primarily to changes in the natural emissions of carbon dioxide from magmatic arcs, volcanic spreading centers, and hot spots, all of which were more active than they have been in the recent geologic past. Other factors such as continental geography, albedo, and ocean circulation and heat transport have played important roles as well. Ocean drilling will provide the material needed to 1) define the scale of these past changes in climate, 2) help determine if greenhouse gases have been solely responsible for the long and short-term changes in Earth's climate, and 3) characterize ecosystem response to climate change on both regional and global scales. This experiment thus focuses on the large changes in global environments associated with geologic and biotic boundary conditions vastly different from those at present. The forcing functions include tectonism, (mountain uplift, weathering, and erosion), volcanism (changing rates which affect global chemical cycles), biotic evolution (which mediates chemical evolution of environments), and catastrophic events such as meteorite impacts.

Objectives

To better understand the operation of the climate system in radically different states, and it's linkages to tectonism, volcanism, and carbon dioxide forcing, we must develop synoptic reconstructions of critical time intervals of the last 120 m.y. These reconstructions should consist of quantitative estimates of climate and boundary conditions on a global scale, including the planetary temperature gradient, ocean chemistry and sedimentary fluxes, and the modes of ocean and atmospheric circulation. The rates of change must be well defined, especially in the cases of relatively abrupt shifts in climate.

To accomplish these objectives we must obtain geographic arrays of continuous long time series in ancient sedimentary sequences with well defined orbital cycles to constrain sedimentation rates. We must precisely define past changes in the concentration of key greenhouse gases. Some progress has been made in this area, but more reliable data are needed, particularly for the episodes of extreme global warmth. We must identify and constrain other major processes involved in the carbon cycle which may act to either dampen or enhance changes in atmospheric carbon dioxide. This includes, on long-time scales, the weathering and burial of carbonate and organic-carbon rich rocks, and on short time scales, ocean-
atmosphere circulation and marine productivity.

To find the causes and mechanisms of past global warmings, the synoptic reconstructions of global climate and ocean chemistry must be combined with a strategy of numerical modeling. In this combined strategy of measurement and modeling lies the relevance to future environmental change. Only by testing predictive models on radically different climatic situations can we be sure that their construction and necessary simplifications are reliable.

Under this experiment we suggest concentration on discrete intervals of time when the climate system was radically different from the present, or when the climates were changing rapidly. Examples of different states include warm episodes in the early Pliocene (3.5 to 4.5 Ma), early Eocene (52-57 Ma), and mid-Cretaceous (91-115 Ma), and glacial intervals of the early and middle Oligocene (33 - 36 Ma) and Pleistocene. Examples of abrupt shifts in climate include global warming in the latest Paleocene (55 Ma), expansion of ice-sheets on Antarctica in the earliest Oligocene (36 Ma), and the inception of the Pliocene/Pleistocene glacial intervals (~3 Ma). In addition, discrete anomalous events such as the Cretaceous/Tertiary boundary (65 Ma), perhaps due to either massive volcanism or meteorite impact, are relevant to this experiment.

Drilling can recover the sedimentary record required to address the following questions:

Were Cretaceous and early Cenozoic episodes of moderate to extreme global warmth tied to greater emissions of CO2 associated with volcanism at magmatic arcs, hot spots (super plumes), and rifted margins (flood basalts), or was global warmth associated with changes in oceanic and atmospheric heat transport?

Was the onset of Antarctic glaciation caused by the increased thermal isolation of Antarctica as Australia drifted gradually northward, or was it caused by more rapid CO_2 feedback?

Are the Antarctic ice-sheets inherently stable or over the last 40 Ma?

What is the role of warm salty bottom water formation in subtropical marginal seas in maintaining warm climates, and how do biogeochemical cycles respond to this mode of circulation?

Has the climate system responded rapidly to gradual forcing due via climatic "thresholds" and feedbacks, or must forcing be rapid to generate rapid large-scale climate change?

Do changes in continental topography and mountain building influence climate by altering atmospheric circulation patterns?

Does mountain uplift increase global chemical weathering rates, and hence the cycling and concentration of atmospheric carbon dioxide, or is the mountain effect only important for physical weathering?

How do catastrophic events such as meteorite impacts or massive volcanic events influence global environments? Are changes reversible or irreversible?

State of the Art

Ocean drilling has contributed significantly to defining the character and timing of long-term changes in the global environments. Two major forcing functions predominate. Volcanic activity affects the levels of greenhouse gases, primarily CO_2. Tectonism affects continental positions and topography, and the location and size of oceanic gateways.

xxx add continental weathering. Use example of asian monsoon evolution.

Drilling has demonstrated that large ice-sheets first appeared on Antarctica in the Oligocene some 40 to 45 Mya, and have remained ever since. During this time, the north Pacific may have been a major source of deepwater formation, in contrast to today. In the time prior to the Oligocene and extending back to at least 120 Ma the oceans were relatively warm and dominated by lengthy episodes of moderate to extreme warmth at high latitudes. Ice-sheets were non existent, sea levels were higher, bottom water was warm, salty, and nearly depleted in dissolved oxygen. These were periods of widespread global volcanism characterized by either the formation of large oceanic plateaus, increased plate subduction, or rifting of continents. The transitions between warm or cold climates were not always gradual, as might be expected under gradual forcing, but sometimes occurred rapidly. The recognition of these rapid shifts and associated transitional climates has given rise to theories on climatic thresholds and feedbacks capable of accelerating and/or amplifying climatic transitions. Identification and quantification of mechanisms that maintain climatic stability, and feedback processes that induce rapid change under radically different climatic states is central to the mission of OHP.

We now have the background to design focussed drilling experiments regarding the factors that drive long term changes in global climate. With the recognition of well defined orbital cycles in pre-Neogene sediments, it will be possible with double and triple coring to correlate between holes and sites with greater precision and construct higher resolution forward climatic records for the Paleogene and late Cretaceous. We also know that by drilling depth transects in several key locations, the vertical and horizontal water mass distributions can be determined. This strategy will provide critical insight into alternative modes of ocean circulation. This approach has worked well in Neogene sediments and needs to be extended back into the Cretaceous. We have also learned that reconstructing Antarctic glacial history requires coring not just on the margins where sequences tend to be incomplete due to erosion and difficult to date, but on nearby submarine highs that are too distant to be eroded by ice-sheets, but near enough to receive ice-rafted sediments from icebergs produced by those ice-sheets.

Near-term Implementation (1994-1998)

The next several years of planned ocean drilling will document only a few aspects of long-term ocean history needed to evaluate the role of tectonism and volcanism in climate change and better define how the climate system responds to warming. Some drilling will focus on obtaining sediments needed for reconstructing changes in tropical climates. This includes drilling in the western equatorial Atlantic to obtain records extending back 35 m.y. and in the Caribbean back 80 m.y. These studies are critical since current climate theory suggests that with future increases in greenhouse gas levels, the high latitudes will undergo extreme warming while the tropics remain more or less stable.

Medium-term Implementation (1998-2003)

In the period from 1998 to 2003, drilling efforts should be focused on obtaining material necessary for 1) defining the extent of pre-Neogene climate change in both the low and high latitude Pacific Ocean, 2) defining the timing and scale of major episodes of volcanism in the Pacific, 3) reconstructing past changes in ocean and atmospheric carbon dioxide levels, and 4) developing a high resolution astronomical time scale in Paleogene sediments for the purpose of better constraining rates of change. Because of the Pacific's' immense size, to fully characterize changes in global climate, the climate record of this basin must be well understood. During previous drilling, very little well preserved, unlithified sediment suitable for building geochemical and paleontologic based reconstructions of the Cretaceous and early Eocene greenhouse worlds was collected from the Pacific Ocean. This was due primarily to the fact that much of drilling focused on obtaining high resolution Neogene sequences, and it was unclear where well preserved Paleogene and Cretaceous material could be recovered.

As a result, a program of drilling is required that specifically targets Paleogene and late Cretaceous sediments. Drilling efforts should be concentrated on obtaining sequences from the 1) western equatorial Pacific, 2) the high latitude Bering Sea, and 3) the Pacific sector of the Southern Oceans, particularly the southwestern Pacific east of New Zealand.

xxx need to explain why. Low-latitude drilling should build a north to south transect across the equator between 30 N and 30 S paleolatitudes. Where possible, a drilling strategy should be employed that involves using previously drilled holes and high resolution seismic stratigraphy to identify regions where Paleogene and Cretaceous sediments outcrop or have a relatively thin Neogene overburden, to minimize problems of sediment diagenesis. Another requirement will be to either, 1) find a means of penetrating cherts without compromising recovery of sediments, or 2) develop a strategy using high resolution seismic stratigraphy to locate gaps in chert layers.

New Era of Scientific Ocean Drilling - Post 2003

With background gained between 1994 and 2003, the new era of drilling will by ready to address more focused questions of long-term climate change. Several problems must be addressed including 1) establishing the existence of alternative modes of ocean circulation, specifically the presence of warm saline bottom waters, 2) locating the major sources of these bottom waters, 3) defining the short and long-term glacial history of Antarctica. The first and second of these problems must be addressed by building 3 dimensional reconstructions of deep water chemistry. This will require vertical depth transects in key locations of the world oceans. To date only one vertical depth transect with more than two sites and complete recovery has been drilled for the pre-Neogene, this was on Ceara Rise, and only included the Oligocene. Other regions where similar depth transects are required include the northwest Pacific, the sub-Antarctic Indian Ocean on Kerguelen Plateau, the south Atlantic sector of the southern oceans on Maud Rise, where the first evidence of warm saline bottom waters was obtained, but where only 2 sites were drilled, and the north Atlantic ocean. Ideally, each of these depth transects must consist of 4 sites which sample 1500 m of water column between 2500 and 4000 m paleowater depth. The third problem will require additional drilling in the circum-Antarctic Southern Ocean. Previous drilling provided a tantalizing glimpse of this regions climatic sensitivity.

OHP Experiment 4: Causes and Consequences of Global Sea Level Change

Scientific Justification

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

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

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

Objectives

Two primary questions that must be answered regarding sea-level change are: 1) are the apparent rises and falls of sea level seen in near-shore deposits around the world synchronous (and therefore evidence for eustasy), and 2) what is the magnitude of any such rises and falls. Knowing the answer to these two questions will allow us to develop strategies for testing what mechanisms are likely controlling the observed character of these depositional packages, and evaluating the impact of sea level change on climate, ocean chemistry, and ocean circulation. *xxx more to be written.*

State of the Art

Work to date on such sequences suggests that fluctuations in sea-level occur much more frequently, and on too short a time sale, to be explained by tectonic mechanisms for changing ocean basin volume. Other viable mechanisms for the creation of these depositional packages have been proposed (for example, current or climate control); however, the testing of such models of depositional control is still in its very early stages. *xxx more to be written.*

Near-term Implementation (1994-1998)

Testing the reality of events on the global sea-level scale requires information from all ocean basins and both hemispheres. And, because sea-level changes have their greatest direct effect on shelf sediments, testing the Sequence Stratigraphic Model requires drilling complete passive margin drilling transects. There is a therefore a need to encourage the development closely integrated sea-level proposals spanning both the process interests of SGPP and the ocean history interests of OHP, perhaps via the mechanism of an informal dual-panel working group. The overall history of sea-level fluctuations is so complex that no singletechnique, or single drilling leg, can be expected to provide a global picture of sea-level variations.

Medium-term Implementation (1998-2003)

New Era of Scientific Ocean Drilling (post 2003)

IV. COMMON THEMES AND PRIORITIES FOR IMPLEMENTATION

xxx to be written

OHP sees a limit to effective implementation of its long-range plan, which needs to be addressed by national funding agencies. In the past, exploratory drilling has been supported by site survey data acquired over the past 30-40 years. This reservoir of information is now running dry. A new, more focused strategy for experimental drilling requires better site survey, including high-resolution digital seismics with high spatial resolution, better knowledge of bathymetry, and preliminary study of sediments using short survey cores. New survey data is thus a prerequisite to new drilling. Early funding of site survey is critical to the success of focused drilling strategy. OHP urges additional efforts in this direction.