The Role of ODP Drilling in the Investigation of Global Changes in Sea Level

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EXECUTIVE SUMMARY

Global sea-level changes affect climate, ocean chemistry, ocean circulation, floral and faunal boundaries, biologic evolution, sediment deposition, global ice budgets and distribution of mineral and petroleum resources. Few phenomena in the earth sciences are as ubiquitous and pervasive in environmental processes.

Clearly, the understanding of global sea-level change is a first-order priority in global environmental studies. Its impact on earth history, solid earth processes, climate and hydrologic systems has been recognized by the U.S. Committee on Earth Sciences, the Second Conference on Scientific Ocean Drilling, and other planning and policy committees in the U.S. and elsewhere.

Marine sediments record effects, proxies and linkages of global sea-level change that range from the obvious, such as erosion of continental shelves during sea-level lowstands, to the subtle, such as minute changes in ocean chemistry. The nature of the earth's response to sea-level change varies: shelfal clastic sediments respond with altered depositional patterns; shelfal and atoll carbonate sediments respond with increasing growth during highstands, and with dissolution and chemical alteration during lowstands; deep-sea sediments respond with changes in chemical and biological proxies filtered through effects of ocean circulation, climate and ocean chemistry. Ocean drilling is critical to the investigation of sea-level change as it constitutes our only tool capable of adequately investigating this diversity of response.

A workshop convened in El Paso, Texas on October 24-26, 1988 under the auspices of JOI/USSAC addressed the scientific and operational problems associated with the use of ocean drilling in the investigation of global changes in sea level. The workshop identified principal objectives, targeted time intervals for detailed study, and suggested a drilling strategy summarized below.

Principal Objectives

- **Determine the synchroneity of globally correlative sequence boundaries.**

- **Determine whether or not globally synchronous unconformities are, in fact, caused by sea-level changes.**

- Determine amplitudes of sea-level changes with an accuracy of 1-5 meters.

- Determine rates of changes of global sea-level changes, and

- Establish interrelationships between sea-level change, ocean circulation, ocean chemistry, climate and other global environmental phenomena.

Targeted Time Intervals

- Neogene "Icehouse" Earth (Late Oligocene-Middle Miocene). Most or all major sea-level changes during this period are thought to be global and glacially driven.

- Cretaceous "Hothouse" Earth (Aptian-Coniacian). This time includes major sea-level changes with no known glaciation. The mechanism(s) responsible for these sea-level changes is not known.

- Paleogene "Doubthouse" Earth (Latest Paleocene-Middle Eocene). This is a period of glaciation to some and non-glaciation to others which contains two widely recognized unconformities whose driving forces have not been identified.

Drilling Strategy

- Drill three or four passive margin transects in each of the three time intervals.

- Drill Cretaceous atolls and guyots.

- Drill deep sea sections beneath oceanographically sensitive sites, and

- **Distribute sites over a wide geographic range.** North-south Atlantic and an east-west low-latitude "megatransects" are recommended for this purpose.

Seven or more legs will be necessary to complete the program.

We believe the proposed program represents an optimum solution to the challenge of investigating a first-order global environmental problem through scientific ocean drilling.

INTRODUCTION

The emerging evidence for global synchrony of changes in sea level throughout much of geologic time is one of the most exciting scientific developments of the past 15 years. Linkages between global sea-level changes, climate, ocean chemistry, ocean circulation, floral and faunal boundaries, biologic evolution, depositional sequences, global ice budgets and hydrocarbon source rock distribution are becoming evident. Application of sea-level models to seismic interpretation has revolutionized the interpretation of seismic reflection data and is having a major impact on the mapping of sedimentary rocks on land.

Nonetheless, much remains uncertain about sea-level changes. Correlations are often controversial, regional sea-level changes may have been misidentified as global events, mechanisms are uncertain and adequate age dating is sparse.

This report summarizes the deliberations of a three-day workshop on the use of ocean drilling for the investigation of sea-level changes and its potential for solving major questions regarding global sea-level changes.

National and international committees, panels and conferences, *e.g.*, the Committee on Earth Sciences (CES, 1989, in press) and the Second Conference on Scientific Drilling (COSOD-II, 1987), have recognized the importance of sea-level studies. The Committee on Earth Sciences sees global sea-level change as a major component in the U.S. Global Change Research Program (CES, 1989, in press). ODP drilling as discussed herein contributes in various ways to all CES strategic priorities (Table 1), *e.g.*, it supports a broad U.S. and international scientific effort, it helps identify natural and human-induced changes in our environment, it requires interdisciplinary science and it allows the scientific community to share financial burdens, use the best resources and encourages full participation of the community.

Sea-level studies are identified as a key segments in CES science elements:

- <u>Earth System History</u>
- <u>Solid Earth Processes.</u>

Strategic Priorities	Integrat. Priorities	Science Priorities						
		Climate and Hydrologic Syst.	Biogeochemical Dynamics	Ecological Sys. & Dynamics	Earth Sys. History	Human Interactions	Solid Earth Processes	Solar Influences
Support Broad U.S. and International Scientific Effort	Documentation of Earth System Change	Role of Clouds	Bio/Atm/Ocean Fluxes	Long-Term Measurements of Structure/Function	Paleoclimate	Data Base Development	Coastal Erosion	EUV/UV Monitoring
Identify Natural and Human-Induced Changes	Observational Programs	Ocean Circulation and Heat Flux	Atm Processing of Trace Species	Response to Climate and Other Stresses	Paleoecology	Models Linking: Population Growth & Distribution Energy Demands Changes in Land Use Industrial Production	Volcanic Processes	Atm/Solar Energy Coupling
Focus on Interactions and Interdisciplinary Science	Data Management Systems	Land/Atm/Ocean Water & Energy Fluxes	Surface/Deep Water Biogeochemistry	Interactions between Physical and Biological Processes	Atmospheric Composition		Permafrost and Marine Gas Hydrates	Irradiance (Measure/Model)
Share Financial Burden, Use the Best Resources, and Encourage Full Participation	Focused Studies on Controlling Processes and Improved Understanding	Coupled Climate System & Quantitative Links	Terrestrial Biosphere Nutrient & Carbon Cycling	Models of Interactions, Feedbacks, & Responses	Ocean Circulation & Composition		Ocean/Seafloor Heat & Energy Fluxes	Climate/Solar Record
	Integrated Conceptual & Predictive Models	Ocean/Atm/Cryosphere Interactions	Terrestrial Inputs to Marine Ecosystems	Productivity/Resource Models	Ocean Productivity		Surficial Processes	Proxy Measurements and Long-Term Data Base
					Sea Level Change		Crustal Motions & Sea Level	
					Paleohydrology			

Table 1. U.S. Global Change Research Program Priority Framework (CES, 1990).

Sea-level studies also contribute to major segments within the CES science element:

- o **Climate and Hydrologic Systems.**

COSOD-II identified sea level changes as one of two priority problems in the area of "Changes in the Global Environment." The other was the closely associated problem of Paleoclimate. Much of what follows in this report has roots in the COSOD-II discussions.

Global sea-level change plays an important role in the search for a *Unified Theory of Planet Earth* (ACES, 1988), a theory that can provide an understanding of earth processes sufficient to construct detailed quantitative and predictive models of earth processes. The plate tectonics paradigm has provided important insight into lithospheric and asthenospheric processes on a global scale; the study of global changes in sea level, on the other hand, can provide new insights into litho-hydro-bio-atmosphere interactions. The interrelationships of sea level, climate, tectonics, ocean circulation and sedimentation are especially important and suggest that a study of sea-level changes can be of far-reaching importance.

Sea-level studies to date have for the most part benefited geologists and geophysicists deciphering the sedimentary rock record from outcrop and subsurface data. In the longer term, the impact of global sea-level changes on paleoclimate, paleoceanography and paleoceanographic chemistry may be more important. For example, at extreme sea-level lowstand (*ca.* 100 m below m.s.l.), exposure of continental shelves increases the percentage of the world's land area from the present 29% to 35%. This change significantly alters the earth's albedo, reduces deposition of calcium carbonate on continental margins, and causes major changes in ocean circulation. Conversely, at extreme highstand (*ca.* 100 m above m.s.l.), the land area is reduced by almost 50%. This also causes major changes in hydro-bio-atmosphere interactions.

Studies of global CO_2 and near-term calculations of atmospheric temperatures suggest that in as little as 50 to 100 years, significant rises in sea level could seriously impact coastal habitats throughout the globe. The record of sea-level changes and accompanying environmental changes preserved in marine sedimentary rocks provides baseline information on a scale of 10^5-10^8 years regarding similar changes in the past. These data would be of significant value in assessing effects of future sea level changes.

As with many developing paradigms, much about sea-level change is understood either poorly or not at all. For example, we have no adequate mechanism other than continental glaciation to explain short period (<10 m.y.) sea-level excursions, while many inferred sea-level changes have taken place during periods with no known glaciation. We understand very poorly the linkages with important global environmental changes and considerable controversy exists regarding details of application of sea-level changes in stratigraphic analysis. Consequently, we expect studies of sea-level change to lead to important discoveries relating to global tectonics and global environmental processes.

Solving the sea-level change riddle will not be easy. Sea-level changes result from complicated interactions between sediment supply, tectonics, climatic changes and eustasy. Separating and measuring eustatic and non-eustatic components of timing, rates of change, and amplitudes are not simple matters. Such an investigation requires the participation of geologists, geophysicists, organic and inorganic chemists as well as botanists and zoologists, well-logging specialists, and representatives of engineering disciplines. Clearly, understanding the history of global sea-level change is a scientific problem of the first order that merits a major effort on the part of the oceanographic, earth and atmospheric sciences communities.

Academic ocean drilling is central to the investigation of global changes in sea level because of its ability to continuously core and collect undisturbed samples from sequences of the marine sedimentary rock record. The availability of marine seismic and well data from the petroleum industry greatly enhances the value of drilling data, and permits the planning of ocean drilling on a scale broader than that usually possible on land.

Subsequent sections of this report summarize the organization of the workshop and report conclusions of working groups addressing problems pertinent to drilling in the deep sea, on clastic margins, on carbonate margins, on carbonate platforms and on atolls and guyots. The report concludes with consensus recommendations and a strategy for drilling for the Ocean Drilling Program.

WORKING GROUP REPORTS

The participants (see Appendix I) devoted the first day of the meeting to a series of talks reviewing the state-of-knowledge regarding sea level changes (see Appendix II). On the second day, participants were asked to join one or more of three *ad hoc* working groups. These working groups addressed the three main geological divisions of the sea floor from the point of view of sea level studies. These were, respectively, the Deep Sea (WG-1), Clastic Margins (WG-2) and Carbonate Margins, Atolls, and Guyots (WG-3). The reports of these working groups follow in subsequent subsections of this report.

At the end of three days of review and discussion, the working groups assembled to compare conclusions and to identify major, consensual problems, objectives and targets. The results of this discussion were merged and form the basis of the Conclusions and Recommendations included at the end of the working group reports.

A number of potential drilling targets, drillsites and locales were also discussed. Data available to participants was generally fragmentary and suggestive rather than conclusive. Thus, these discussions were intended to encourage potential investigators to consider the development of drilling proposals in those areas where further investigation shows merit, rather than specifically recommending areas and local sedimentary sections as drilling targets. These discussions are summarized in Appendix III.

WORKING GROUP 1

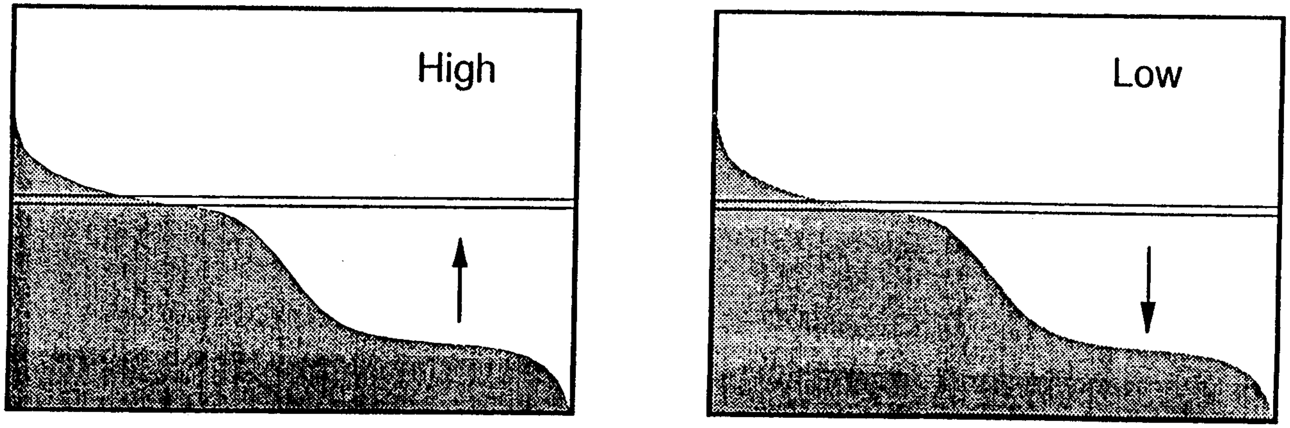
DEEP SEA

Introduction

The deep-sea sedimentary record contains subtle but valuable expressions of sea-level change. Unlike margin, platform and atoll records representing relatively direct responses to rising and falling sea levels, the deep-sea record contains indirect responses reflected in the histories of changing ocean chemistry, circulation and climate. The deep-sea record also reveals changes in ocean chemistry, circulation and climate that may have contributed to sea-level change. The causes/effects of sea-level fluctuations encoded in deep-sea sediments allow us to examine the global signal of sea-level change free of local influences and provide an opportunity to gain critical insight into the response of the earth/ocean system to a key component of global change.

A change in sea level of *ca.* 100 m would have an immediate effect on approximately 15% of the earth's surface represented by the near-horizontal portion of today's hypsographic curve. This change would affect the entire global environment -- the atmosphere, hydrosphere, sedimentary lithosphere and biosphere. Directly, as well as indirectly through feedbacks between these subsystems (**Fig. 1**), deep-sea sediments record the history of this entire earth system. Obviously, these processes, events and feedbacks will yield different products in different basins and at different latitudes, and small changes may not show at all. Nonetheless, rapid sea-level changes, whatever their cause, will punctuate the record of geo-biospheric change. The effects of sea-level change and their expression in the sedimentary record are complex and manifold. Below, we outline several of these complex relationships.

Extended shallow seas during periods of high sea level change the oceanic heat reservoir, whereas increased albedo during lowstands makes for a cooler earth with stronger temperature gradients. These changes are recorded in changes of species associations, phenotypes and the oxygen isotopic composition of calcareous skeletons.



Global Environment				
Element	Sub-element	High sea-level effect	Low sea-level effect	Encoder; Proxy
Climate		warm low T° gradient	cool high T° gradient	$\delta^{18}O$, biota
Ocean Circulation	surface bottom	stratified slack	mixed vigorous	$\delta^{13}C$, TOC biota
Productivity		oligotrophic	eutrophic	$\delta^{13}C$, biota
Life	plankton	efficient speciation high diversity	opportunistic extinction low diversity	biota
Chemistry	CCD silica	shallow low	deep high	sed. composition sed. & skeletal composition
Sediment	accumulation grain size magnetic minerals aeolean components	low rate fine low low	high rate coarser high high	age-thickness grain size magnetic intensity grain composition
Hiatuses		starved	mechanical	stratal pattern

Figure 1. Selected effects of sea level high- and lowstands in open ocean conditions and the deep sea record (modified from Caron and Homewood, 1983).

Sea-level changes influence oceanic circulation patterns. One would expect mixed surface waters and enhanced thermohaline circulation during lowstands to be recorded in the distribution of biota, the difference in $\delta^{13}C$ of benthic versus planktonic skeletons, and a lack of preserved organic matter.

These same signals allow for estimates of past primary organic production. During lowstands, dissolved nutrients reach the open ocean in especially large amounts, whereas they are trapped on the shelf during highstands which minimizes nutrient recycling. With maximum organic and carbonate production on the shelf during times of high sea level, the ocean is starved and the carbonate compensation surface will shoal. The opposite will happen during sea level lows. Yet, regional changes in circulation patterns may cause the opposite to occur.

Sea-level changes have a profound effect on the biosphere. Eutrophic conditions during low stands generally support low diversity assemblages and opportunistic species. Mixing of the surface layers and reduction of the shelf area lead to destruction of planktonic and benthic niches and hence to isolation or extinction. Conversely, sea-level rises open niches, enhance migration and lead to radiation (speciation). Thus, sea-level changes punctuate evolution.

Finally, the overall distribution of marine sediments is a record of sea-level change. In its low sea-level mode, the ocean receives a maximum of terrigenous detritus as well as planktonic skeletal material. These result in high accumulation rates of relatively coarse sediments rich in magnetic minerals, eolian components, and, at times, ice rafted debris. The record in its high sea-level mode may be incomplete because of near total starvation during times of maximal continental flooding, or because of erosion/non-deposition resulting from enhanced bottom current velocities. These non-depositional and erosional events can be distinguished by stratal geometry revealed by high resolution seismic profiles.

The record of sea-level change in margin, platform and atoll sequences is derived largely from the study of unconformable surfaces. Shallow-water sequences record the timing, magnitude and rate of sea-level change, but provide limited information about these mechanisms and their effects on the state of the earth/ocean atmospheric system. This is because material representing these times is missing from the shallow-water record. The deep-sea record, on the other hand, can provide a nearly continuous history of the earth/ocean system through sea-level events. The deep-sea record thus represents the ultimate correlative conformity.

The approach we propose is a classic paleoceanographic study of the deep-sea sedimentary record that calls on the analysis of a number of physical, chemical and biological proxies that serve as indicators of change in the atmosphere and ocean. On their own, these studies generate the time series of oceanographic and climatic change that are fundamental paleoceanographic tools. In the context of sea-level studies, they provide the opportunity to examine the response of the system to events well- documented from margin, platform and atoll studies, and offer insight into the ultimate causes of sea-level change. Before deep-sea sediment studies can be placed in a sea-level context, however, we must establish the correlation between margin- and atoll-derived events and the deep-sea record. The degree to which these correlations can be made will be critical in determining the potential of the deep-sea record for providing the necessary data on mechanisms of sea-level change and on response of the global system to such changes.

Perhaps most importantly, studies of direct indicators of sea-level changes and their proxies in the deep sea are expected to show the interrelationships of sea-level change to ocean circulation, ocean chemistry, climate and other major environmental phenomena. In this respect, deep-sea studies are essential to the overriding objective of studies of global change, that of a *Unified Theory of Planet Earth.*

Major Objectives

Major objectives outlined by the Deep-Sea Working Group are observational, aimed at delimiting the response of the earth/ocean system at times of sea-level change. Critical to meeting these objectives are methodological improvements, particularly in stratigraphic resolution and isotopic work, that will permit detailed correlations and more direct indications of causes and magnitudes of sea-level change.

Three major questions require answers if deep-sea studies are to contribute significantly to studies of global sea-level changes. These are:

- What are the timing, rate of change and nature of sea-level changes expressed in the deep-sea sedimentary record?
- To what extent are deep-sea sequences and other sea-level proxies synchronous in different ocean basins?

- What, if any, are the direct indicators of sea-level changes in the deep sea?

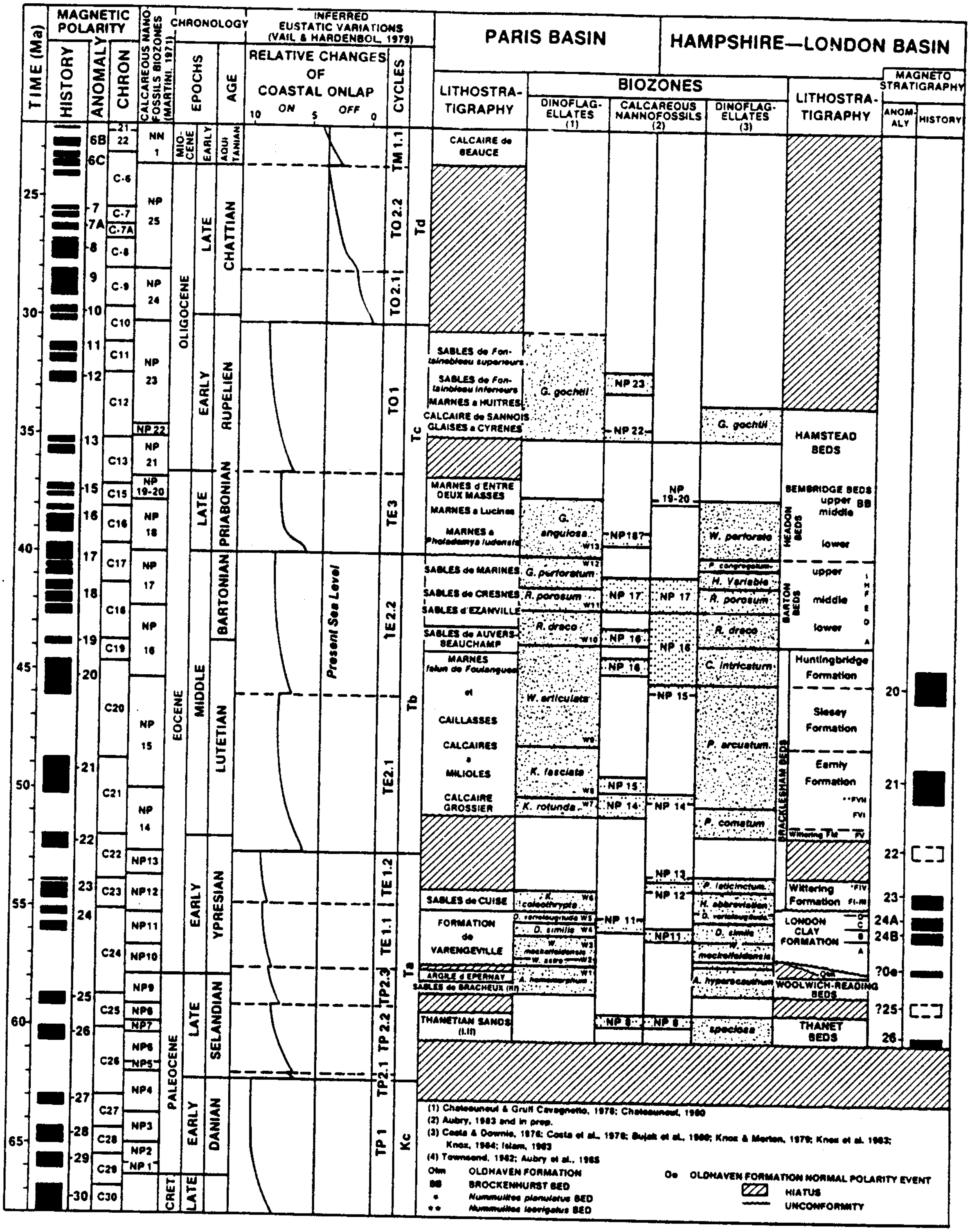
The following summarizes recommended strategies for answering these questions.

Measure the Timing, Rate and Nature of Sea-Level Changes

We must establish the limits of resolution in correlating deep-sea and margin/platform events. Presently, it is not clear whether deep-sea and margin events are synchronous or phase-shifted in some manner. We need to identify those regions and time intervals where we can obtain maximum resolution and improve our ability to make correlations. A geochronologic framework is essential for understanding and estimating rates of geological processes as well as for establishing the synchrony of events. There are several components which are fundamental to a truly integrated time-scale; these include biostratigraphy and biochronology, isotopic dating, magnetostratigraphy and sea-floor spreading magnetic lineations (Aubry *et al.*, 1988). The integration of these various techniques is now leading to high resolution correlations between marginal/platform and deep-sea stratigraphies. A good example of this approach is that by Aubry (1985, 1986) and Aubry *et al.* (1986), in which the classic English Paleogene stratigraphic succession developed on the NW European passive continental margins has been correlated with the marine deep-sea stratigraphic record by means of an integrated magnetobiostratigraphic approach (**Fig. 2**).

In a recent investigation of the major unconformity and postulated sea-level fall across the lower/middle Eocene boundary (Vail *et al.*, 1977), Aubry (in press), using this integrated approach, has been able to achieve a chronologic resolution of less than 0.1 m.y. in estimating the age of the upper and lower surface of this unconformity at ODP sites 612 and 613 (New Jersey continental margin; see **Fig. 3**).

Of particular interest in future high-resolution chronology are recent advances in laser fusion $^{40}Ar/^{39}Ar$ dating which allow dating of volcanic minerals as small as single crystals. Both potassium and argon measurements can be obtained simultaneously from the same small sample. It is also possible to determine different age components of contaminated tephra by this method. Increased precision and accuracy in dating through multiple analyses may be expected as a result of the relatively short time (less than a half hour) required to date a sample.



(1) Chateauneuf & Gruff Cavagnetto, 1978; Chateauneuf, 1980
(2) Aubry, 1983 and in prep.
(3) Costa & Downie, 1976; Costa et al., 1978; Bujak et al., 1980; Knox & Morton, 1979; Knox et al. 1983; Knox, 1984; Islam, 1983
(4) Townsend, 1982; Aubry et al., 1985

Olm	OLDHAVEN FORMATION	Oe	OLDHAVEN FORMATION NORMAL POLARITY EVENT
BB	BROCKENHURST BED	▨	HIATUS
*	*Nummulites planulatus* BED	——	UNCONFORMITY
**	*Nummulites laevigatus* BED		

(from Aubry, 1985, Geology, V.13, Fig 2).

Figure 2. Magnetostratigraphic-biostratigraphic correlations between Paleogene deposits of Hampshire-London Basin and Paris Basin (from Aubry, 1985).

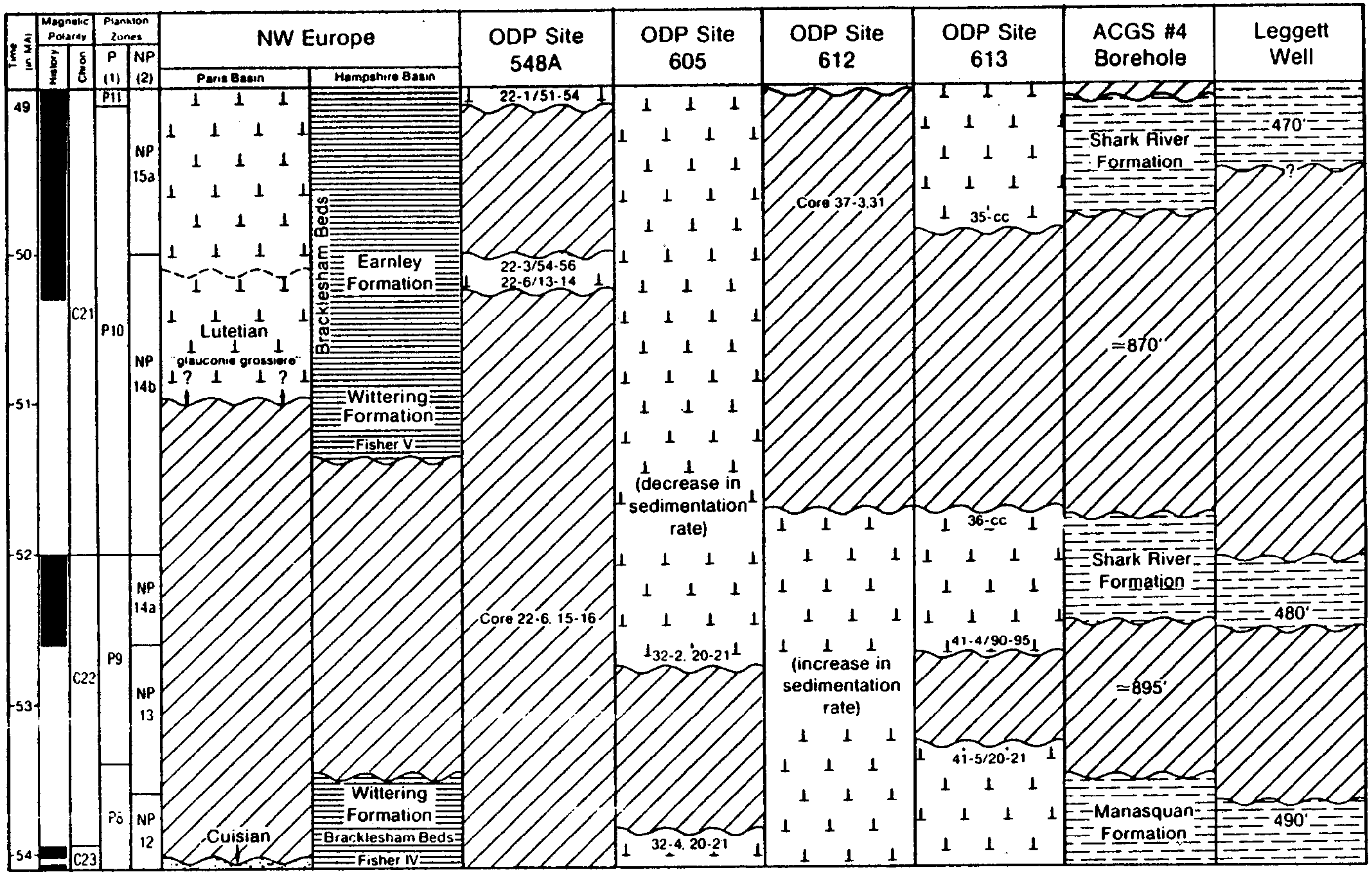


Figure 3. Interpretation of the stratigraphy of the upper lower to lower middle Eocene interval from selected sections with good biostratigraphic or magnetobiostratigraphic control from the North Atlantic basin (from Aubry, in press).

Precision levels of less than 1% are now routinely possible (Swisher *et al.*, in prep.) in the mid-Cenozoic, for example (i.e., errors of ±30,000-50,000 years at 35 Ma are now achievable). The implication for high-resolution correlation is clear. Until now, biostratigraphy and biochronology have been routinely able to achieve a degree of chronologic resolution considerably higher than that of isotopic dating with its inherently large analytic errors. Fusion dating is now capable of providing numerical values for parts of the stratigraphic record with comparable or greater precision than classical biostratigraphy and biochronology. It is clear, now more than ever, that an accurate biostratigraphy is important as we continue to improve upon the geochronologic framework which underlies attempts at high resolution correlation between marginal/platform and deep-sea stratigraphies.

Although it is widely recognized that stratigraphic resolution is critically important to the interpretation of the stratigraphic record (Miller and Kent, 1987; Christie-Blick, 1988), the power of the tools developed over the last decade is largely underestimated at present (Miller and Kent, 1987). The best resolution is derived from integration of various means of correlation, chiefly magnetostratigraphy and biostratigraphies based on diverse microfossil groups. While in theory resolution is infinite in continuous stratigraphic sections, in practice it is limited to varying degrees by the incomplete nature of the stratigraphic record. Because of the availability of temporally close biostratigraphic datums in the upper lower and lower middle Eocene, and because of the especially frequent magnetic reversals in this stratigraphic interval, chronologic resolution to ±100 k.y. (Aubry, in press) can be achieved. Elsewhere in the Cenozoic, resolution of ±500 k.y. or less appears possible. The difficulty in reaching these levels of resolution is not with our chronologic tools, but with the stratigraphic record itself which does not always allow us to apply all chronologic tools simultaneously in a given section. Nonetheless, direct dating of unconformities and evaluation of the duration of hiata are possible at most levels in the Cenozoic. The significance and correlation of stratigraphic sequences can be unravelled to the extent necessary to make significant advances in our understanding the links between sea-level change and the earth/ocean system.

Studies by Burke *et al.* (1982), DePaolo and Ingram (1985), Hess *et al.* (1986), and Miller *et al.* (1987) have shown the potential for using the record of $^{87}Sr/^{86}Sr$ preserved in marine carbonates as a stratigraphic tool. The Sr-isotope ratio in seawater is believed to be constant at a given time, since the residence time is much longer than oceanic mixing times (Broecker and Peng, 1982). The $^{87}Sr/^{86}Sr$ record from the late Eocene to Recent has been one of apparently monotonically increasing values (DePaolo and Ingram, 1985). Thus, measurement of the

$^{87}Sr/^{86}Sr$ ratio in marine carbonates affords a powerful correlation tool for this interval, especially for tying shallow-water sequences to better constrained deep-sea records (*e.g.*, Miller *et al.*, 1987).

Ages can be estimated from the Sr-isotope measurements using empirical age - $^{87}Sr/^{86}Sr$ relationships. Most Sr-isotope records have been correlated to the geological time scale using second- or third-order biostratigraphic correlations (*e.g.*, DePaolo and Ingram, 1985). Biostratigraphic correlations are often complicated by varying taxonomic and stratigraphic interpretations and by diachronous and geographically restricted ranges. Magnetostratigraphy provides a facies-independent means of correlation, and can yield virtually instantaneous temporal resolution in the stratigraphic vicinity of field reversals. For the Oligocene, changes in $^{87}Sr/^{86}Sr$ have been calibrated directly to the Geomagnetic Polarity Time Scale (GPTS; Miller *et al.*, 1987). Given the rate of change of $^{87}Sr/^{86}Sr$ (0.000035/m.y.) and sample reproducibility, stratigraphic resolution for this interval is ±1 m.y. or better (Miller *et al.*, 1987). During the early to early middle Miocene (*ca.* 23-14 Ma), the rate of change of $^{87}Sr/^{86}Sr$ was higher (0.000066/m.y.) than during the Oligocene, and stratigraphic resolution is better (about ±0.5 m.y.; Miller *et al.*, in prep.), while for the late middle to late Miocene (*ca.* 14-6 Ma), the rate of change was lower (0.000016/m.y.) and resolution worse (about ±2 m.y.; DePaolo and Ingram, 1985; DePaolo, 1986; Hess *et al.*, 1986).

Diagenesis is a potential problem, especially in deeply buried sections (Hess *et al.*, 1986). Nonetheless, similar results have been obtained for coeval sections with substantially different burial histories, indicating that diagenetic problems are less severe than anticipated. For example, the excellent comparison between the shallowly buried DSDP Site 522 and deeply buried (over 1,000 m) DSDP Site 516 argues against strong diagenetic overprinting. Similarly, identical results from the Contessa Quarry limestones and these DSDP sites suggests a negligible diagenetic effect (Miller *et al.*, 1987).

Recent studies based on regional correlations of foraminifera and ostracods in the Neogene of Pacific atolls reveal a stratigraphic resolution in this interval of ±1-3 m.y. More importantly, platform sediments (based on work at Enewetak and Belize) contain nannofossils that permit a direct tie between platform and deep-sea zonations (Wardlaw, 1989).

An example of the potential of these techniques is the preliminary correlation of Enewetak hiata defined by nannofossil zones, and a number of equatorial Pacific-wide seismic events. These seismic horizons have been shown to be the result of carbonate dissolution events speculatively associated with sea-level changes (Mayer *et al*, 1986). These correlations, if correct, provide independent evidence of the direct links between sea level, global ocean chemistry and the deep-sea seismic record.

We must also determine the nature (sign, magnitude and rate) of changes expressed by deep-sea proxies. The principal proxies are:

- **Dissolution**, as evidenced by changes in %$CaCO_3$ content, changes in physical properties of sediments, hiata in seismic records, changes in %SiO_2, *etc.*;
- **Productivity**, as indicated by %opal flux, $\delta^{13}C$ amounts, faunal assemblages, and others;
- **Bottom circulation**, recorded in mineralogy, grain size, bed forms, $\delta^{13}C$, Cd/Ca, and other proxies;
- **Surface circulation**, suggested by faunal assemblages, phenotypes, and other data;
- **Sediment flux**, indicated by accumulation rates and suggested by seismic data; and
- **Evolution**, indicated by extinctions, radiations and changes in biostratigraphic assemblages.

Identify Inter-Ocean Phase Shifts

Determining the expression of global sea-level change in the deep-sea record, in terms of the proxies discussed above, is a critical first step in understanding causal mechanisms and earth system responses. The next crucial step is establishing the phase relationships, sequencing and inter-basin differences in the proxy signals. For example, tectonic events (even short term ones) leading to sill deepening can change bottom circulation patterns that in turn may affect global climate and ultimately control sea level. Conversely, externally-driven climatic fluctuations on many time scales change sea level and result in changed bottom circulation patterns. All of these processes are at work; we are faced with the task of sorting them out.

Given adequate correlations among a global array of high resolution cores, determining leads and lags between climate, circulation, and ice volume proxies directly addresses the question of causal mechanisms and ocean responses. While we do not yet have either the correlative ability or the global data array, the potential of this approach is demonstrated by evaluating a single, internally consistent data set (**Fig. 4**).

For example, a close look at the relationship between a seismic, physical property and chemical event identified in equatorial Pacific DSDP cores reveals a clear sequence of events: an isotopic excursion from relatively heavy $\delta^{18}O$ values to relatively light values was followed by an extreme - and brief - carbonate dissolution event. The equatorial Pacific-wide seismic horizon associated with this sequence results from the impedance contrast at the change from high to low carbonate. Our best attempt to determine the position of these events within Exxon's "eustatic sea-level curve" framework (Haq *et al.*, 1987) places the dissolution event within an interval of rapid sea-level rise. Establishing this sequence of events (a shift to isotopically lighter $\delta^{18}O$ followed closely by a dissolution event) appears to support basin-margin flooding as a mechanism for the deep-sea hiatus and reflector formation. With similar information gathered in a range of environmental settings, we can expect to begin to unravel the cause and effect of sea-level change.

The system response is the deep-sea expression of sea-level fluctuations in different ocean basins. Studies of Pleistocene cores, for example, have indicated that glacial episodes (and thus global lowstands) are characterized by high carbonate accumulation in the Pacific Ocean but low carbonate accumulation in the Atlantic; interglacials show low carbonate accumulation in the Pacific and high carbonate values in the Atlantic. These relationships, which may have reversed during certain periods (Dunn and Moore, 1981; Vincent *et al.*, 1985), are not well understood. Their resolution is critical to unraveling the complex interrelationships among dissolution, productivity and sea-level changes.

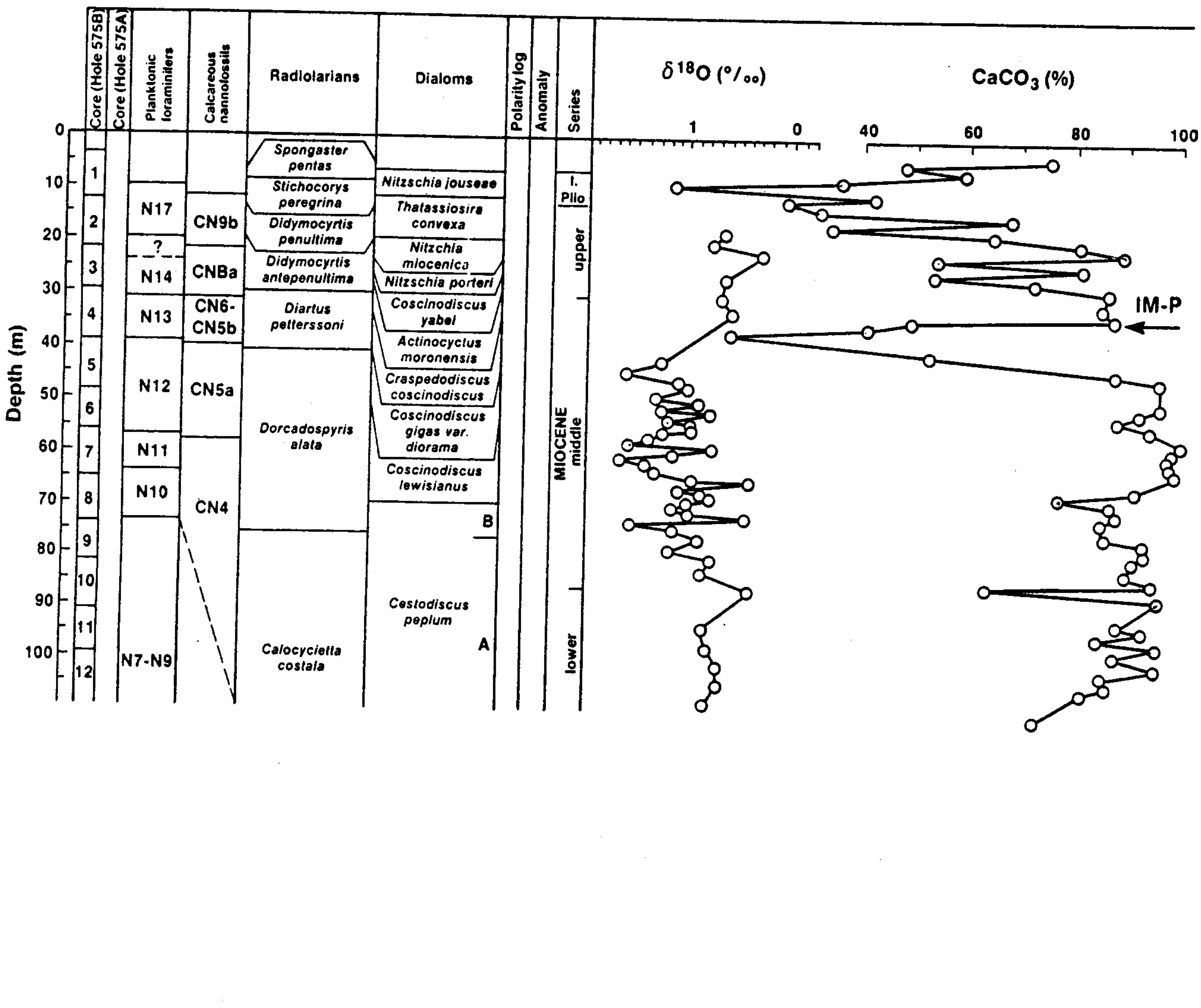


Figure 4. Biostratigraphy, oxygen isotope and carbonate stratigraphy of upper 100 m of DSDP Site 575. IM-P marks position of regionally traceable seismic horizon (from Berger and Mayer, 1987).

Search for Direct Indicators of Sea-level Change

While most of the proxies are one or more steps removed from primary sea-level processes, the Cenozoic oceanic $\delta^{18}O$ record contains information about temperature and ice-volume history closely tied to sea level. The challenge to isolate the ice volume record from the $\delta^{18}O$ signal is a controversial task.

Despite changes in Cenozoic bottom water temperatures, benthic foraminiferal $\delta^{18}O$ records provide some constraints upon ice volume, indicating the presence of ice sheets at least intermittently during the Oligocene to early Miocene and continuously since the middle Miocene (Miller *et al.*, 1987). Western equatorial planktonic foraminiferal $\delta^{18}O$ records suffer less from temperature effects (Matthews and Poore, 1980; Prentice and Matthews, 1988), although these too may reflect changes in temperature through time. The best Pleistocene indicator of ice growth is a coeval increase in global benthic and western equatorial planktonic $\delta^{18}O$ records (Shackleton and Opdyke, 1973). Mid-latitude planktonic foraminifera also record Pleistocene ice-volume changes (Crowley and Matthews, 1983), but efforts to adjust mid-latitude planktonic $\delta^{18}O$ values to equatorial values (*e.g.*, Prentice and Matthews, 1988) are hampered by local variations in sea-water composition and latitudinal temperature gradients through time.

These established principles have been difficult to apply to the Cenozoic $\delta^{18}O$ record since adequate data are lacking in many intervals. For example, no suitable low-latitude planktonic foraminiferal record is available for the Paleogene. However, Oligocene benthic foraminiferal $\delta^{18}O$ maxima at *ca.* 35, 33, and 23 Ma can be directly linked with $\delta^{18}O$ increases in subtropical planktonic foraminifera (Miller *et al.*, 1987) and maxima in ice sheet development inferred from glacio-marine sediments. The early to middle Miocene ice volume signal has not been isolated in part because of problems in correlating the numerous benthic $\delta^{18}O$ records available. Two early to middle Miocene western equatorial planktonic $\delta^{18}O$ records are available: Indian Ocean Site 237 (Vincent *et al.*, 1985) and Pacific Site 289 (Savin *et al.*, 1985; Shackleton, 1982). The record at Site 289 shows little covariance between the benthic and planktonic $\delta^{18}O$ signals; however, the lower middle Miocene section is deeply buried (greater than 500 m) and may have been affected by diagenesis. In contrast, comparison of the Site 237 planktonic record with benthic foraminiferal records shows good agreement in timing and amplitude of $\delta^{18}O$ variations; this may be interpreted as reflecting a substantial ice volume signal (see Fig. 5).

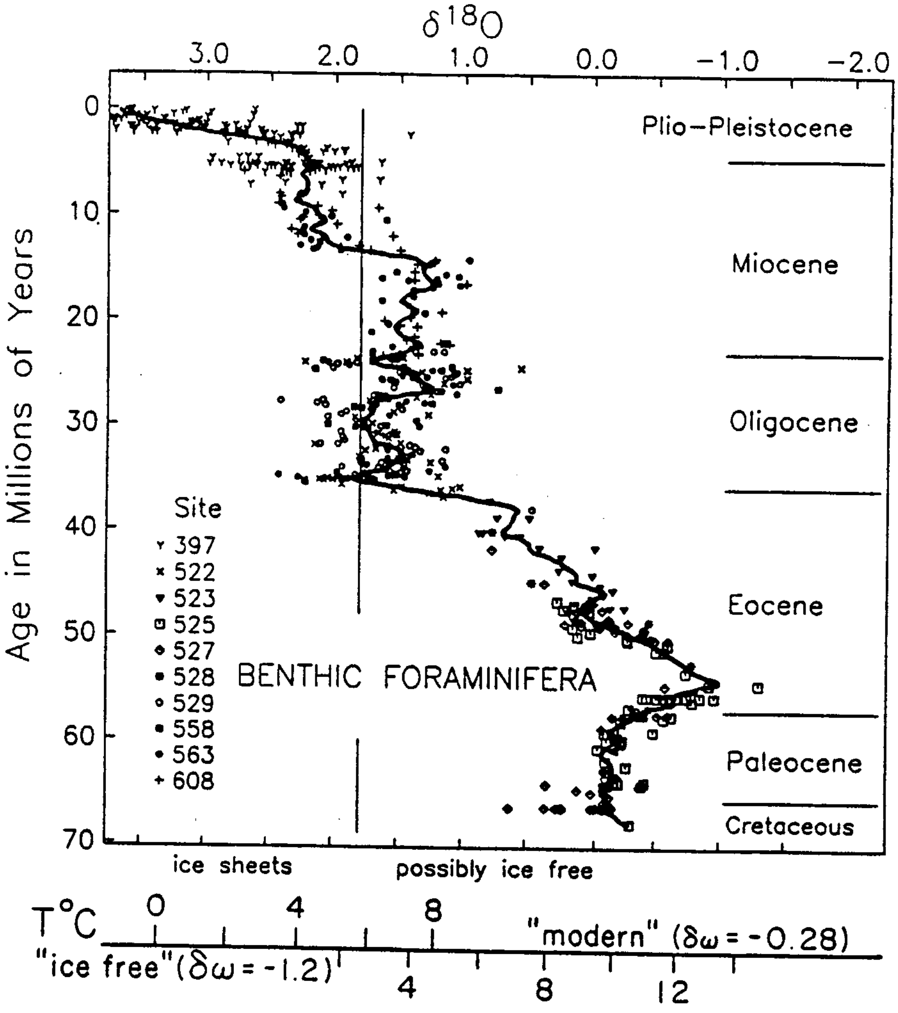


Figure 5. Composite benthic foraminiferal oxygen isotope record for Atlantic ODP sites. The vertical line is drawn at 1.8 ‰; values greater than this suggest the existence of large ice sheets (from Miller *et al.*, 1987).

The Site 237 record is not the full answer, only an intriguing hint, for it suffers from low middle Miocene sedimentation rates (and thus low stratigraphic resolution) as does much of the equatorial Indian Ocean (Duncan *et al.*, 1988).

These examples illustrate the potential of $\delta^{18}O$ records to decipher the record of Cenozoic glacio-eustatic changes, particularly when using western equatorial planktonic foraminifera. In this quest, we are limited by lack of appropriate material.

Hiata, condensed intervals, poor recovery, lack of oriented cores needed for equatorial magnetostratigraphy, and deep burial depths have hindered attempts to obtain continuous western Atlantic equatorial records with proper stratigraphic control. Nonetheless, properly focused programs in these regions can and will yield the requisite sections for unlocking the secrets of the ice house world.

Site Criteria

Deep sea paleoceanographic objectives of a sea-level program require a global array of high resolution sites across critical present and past oceanographic boundaries including both water mass interfaces and oceanic fronts. Site locations should be optimized for recovery of time intervals particularly important to sea-level studies.

Criteria Common to All Sites

- **Continuous recovery** is needed to obtain as complete a record as possible. This requires development of improved coring techniques for sand-rich sediments and for alternating hard and soft lithologies such as chert-chalk sequences.
- **High stratigraphic resolution** requires drilling in areas of high sedimentation rates. This implies sites in equatorial and/or high latitude zones.
- **Excellent biostratigraphic control** is necessary to facilitate correlations. Sites above the calcite compensation depth are preferred.

- **Reliable and detailed magnetostratigraphy,** integrated with biostratigraphy, represents the best correlation tool available. All cores (including XCB) must be properly oriented, especially when located in low latitudes.

Criteria for Ocean Chemistry and Bottom Water Sites

- **Depth transects on equatorial plateaus**. The relative uniformity of sea surface temperatures in these regions minimizes the uncertainties of removing temperature effects from records of $\delta^{18}O$. Candidate sites include:

  Ceara Rise, Ontong Java Plateau (M), 90 E Ridge, Maldives, Walvis Ridge and Manihiki Plateau (M). (M denotes Mesozoic targets.) Other Mesozoic targets include Somali basin, Moroccan basin and Angola basin.

- **Depth transects across bottom water passages (gateways) and across strategically located sediment drifts**. Candidate sites include:

  Norwegian-Greenland Sea - Eric Drift, Rockall region, Tethyan- eastern Mediterranean and Walvis Ridge.

Criteria for Productivity and Surface Water Circulation Sites

- **Transects across present and past oceanic fronts and thermal gradients**. Candidate sites include:

  Equatorial Pacific and Atlantic (eastern) -- Sierra Leone Rise, East Pacific Rise.

  High latitude transects -- Kerguelen, Walvis Ridge, Norwegian-Greenland Sea, Bering Sea (M), Arctic.

- **Margin transects** as described in reports from other working groups.

Criteria for Sediment Flux and Evolution Sites

- Continuous high resolution cores from almost anywhere are appropriate, provided the section includes significant quantities of biogenous sediments throughout.

Drilling Objectives

We propose investigating three time intervals with known and widely spaced fluctuations of relative sea level of probable global significance. The intervals we call "icehouse earth" (Late Oligocene-Middle Miocene; biochronozones P21-N15, Blow, 1969; polarity zones 10-5C, 32-9 Ma, Haq *et al.*, 1987), an interval of widely recognized glaciation; "hothouse earth" (Aptian-Coniacian; biochronozones LC8-UC7, van Hinte, 1976; polarity zones M0-long normal zone 34, 116-87 Ma, Haq *et al*, 1987), an ice-free interval; and "doubthouse earth" (Latest Paleocene-Middle Eocene; biochronozones P5-P10, Blow, 1979; polarity zones 25-21, 55-48 Ma, Haq *et al.*, 1987), a period which may or may not have had waxing and waning ice.

WORKING GROUP 2

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SILICICLASTIC MARGINS

Modern siliciclastic margins contain histories of sea-level change that are unique in several ways: 1) their shallow water sediments are direct indicators of sea-level fluctuations; 2) their records can span as much as 180 Ma and selected intervals can yield temporal resolution of ±1 m.y. or better; and 3) their internal stratal geometry can be clearly imaged and analyzed with seismic reflection profiles.

Introduction

Two Ways to Study Eustatic Change

Two approaches are used to derive histories of eustatic change from siliciclastic margin records. The first is based on mapping lateral shifts in the position of the shoreline, or on gauging water depth changes from biofacies or lithofacies (Bond, 1978; Hallam 1984; Harrison, in press). Unfortunately, both shoreline position and water depth are sensitive to tectonic subsidence and sediment supply as well as to eustatic change. As a result, times of transgressions/regressions or maximum/minimum water depths may not be synchronous among various basins (Pitman and Golovchenko, 1983; Parkinson and Summerhayes, 1985) and other means of deriving eustatic histories from siliciclastic margins are desirable.

The second approach is based on analyzing the distribution and character of regional unconformities (Sloss, 1963; Vail *et al.*, 1977; Haq *et al.*, 1987; van Wagoner *et al.*, 1988). These stratigraphic discontinuities, or "sequence boundaries", represent surfaces of sediment by-pass or erosion that form when depocenters shift abruptly. They represent natural physical boundaries that subdivide sediments into stratigraphic packages. They are characterized by stratal terminations observed in outcrop or detected in the subsurface on seismic reflection profiles. Sequence boundaries of demonstrably basin-wide extent are thought to be caused primarily by a decreased rate of local tectonic subsidence or by an increased rate of eustatic sea-level fall (Vail *et al.*, 1977; Pitman, 1978), and are the result of downward shifts in the elevation of depositional base level. Base level is the theoretical surface separating erosion and/or by-pass from net sediment accumulation; on seismic profiles it corresponds to the point of updip encroachment of strata, or "coastal onlap", onto an underlying sequence boundary. While transgressions and regressions caused by changes in sediment supply can produce minor sequence boundaries, they cannot account for sequence boundaries with marked changes in facies. These types of discontinuities can be caused only by changes in base level.

Sequence Stratigraphy - It's Strengths and Weaknesses

It has been proposed (Vail *et al.*, 1977) that many sequence boundaries are the same age in different basins of the world, and in the absence of any viable mechanism for globally synchronous tectonism, these sequence boundaries must therefore register times of past eustatic change. Several criticisms have been raised with regard to this application to sea-level analysis, and they include:

- Magnitudes of tectonic changes in margin elevations are potentially much larger than eustatic magnitudes, and may overwhelm any eustatic signal embedded within a sequence of depositional units. Consequently, similar basin stratigraphies may indicate similar tectonic histories rather than truly eustatic changes (Watts, 1982).

- The basis for asserting that a eustatic signal can be derived from sequence stratigraphy rests on the similar chronologies of different basins, not on the character of a single, independently analyzed basin; chronostratigraphic resolution cannot demonstrate inter-basin synchroneity to better than ±0.5 m.y. (Miller and Kent, 1987; Kent and Gradstein, 1985), and at present there is no way to determine rigorously any eustatic signal on shorter time scales.

- It is assumed that regional sequence boundaries have uniform chronostratigraphic significance within a given basin, *i.e.*, that everywhere the strata below an unconformity are older than those above; but examples have been described where this does not hold true (Christie-Blick *et al.*, 1990; Tucholke, 1982).

- Seismic profiles of the subsurface can provide regional correlation of sequence boundaries that are difficult to achieve in outcrop studies. The discipline of seismic stratigraphy has developed rapidly over the last 15 years, largely as a result of this valuable contribution to basin analysis. Nonetheless, acoustic resolution places unsurmountable limits on its ability to distinguish closely-spaced reflecting surfaces. For this reason, only "second-order" (*ca.* 10 m.y.)

> cycles of coastal onlap were used in constructing the recently published eustatic curve of Haq *et al.* (1987); third-order (*ca.* 1 m.y.) cycles were derived from log and outcrop data. It has become common practice to establish regional correlations by matching the number of seismic sequence boundaries bracketed by known datum surfaces, even if the critical reflectors cannot be traced between these occurrences. This practice of "pattern matching" does not provide the rigor needed to confirm the correlation of third- and higher-order sea-level events.

Sequence stratigraphy has been taken one step further to provide estimates of the magnitude of eustatic changes (Vail *et al.*, 1977; Posamentier *et al.*, 1988). The procedure requires measuring the vertical component of onlap, termed "coastal aggradation", between the lowest and highest points of onlap within a given sequence. After corrections are made for the differences in sediment compaction, isostatic loading, and thermal subsidence that occurred at these two positions of coastal onlap (Hardenbol *et al.*, 1981), the remainder is taken as the amount of eustatic rise.

This technique can result in significant errors because shifts in coastal onlap are a response to changes in the rate of eustatic change -- not to the magnitude of these changes. Coastal aggradation is therefore a measure of base level change between the times of most rapid eustatic fall and most rapid eustatic rise. Several other considerations complicate the derivation of magnitudes from aggradation, including: 1) Tops of sequences are typically eroded, so that aggradation provides an underestimate of sea-level rise. 2) The upper parts of sequences that have not been eroded consist of alluvial and coastal plain sediments which, if not removed from the measurement, result in an overestimate of sea-level rise. 3) Subsidence and aggradation rates vary across a basin; it is unclear how a single profile can objectively represent a cross section for any given basin.

Strategy

WG2 stipulated a 3-step approach to verifying the influence of eustatic change on stratigraphic records of siliciclastic margins. As with the objectives outlined by the other working groups, technological challenges ensue, as described later in the text.

Step 1: Determine the degree to which regional unconformities are globally correlative.

Three processes are known to affect the accumulation of sediments along continental margins. These are sediment supply, local tectonism and eustasy. Because of their influence on depositional base level, the latter two exert the most control and are primarily responsible for the origin of sequence boundaries, *i.e.*, regional unconformities. In contrast to local tectonism, eustatic changes develop unconformities that ought to be correlative from one margin to another. Hence, the first goal of sea-level research is to establish the degree to which regional unconformities are globally correlative. Those found to match among different continental margins are candidates for further study of eustatic control; the others must be discarded because of the likelihood that they were caused by local tectonism.

Chronostratigraphy provides the most obvious way to establish correlation among margin records. Demonstrating synchroneity is a technical challenge, however, and for two reasons can only be proven within ranges of confidence: 1) chronostratigraphic resolution is presently limited to ±0.5 m.y. for much of the Cenozoic (Miller and Kent, 1987), and ±1-2 m.y. for the Mesozoic (Kent and Gradstein, 1985); and 2) regional unconformities can be located more easily than their correlative conformities, so that often the task is to assess correlation among measurable chronostratigraphic gaps, not among specific time lines.

Continental margins respond to eustatic change in ways and on time scales that depend largely on local factors. Models predict a lag can exist between the time of eustatic change and the resulting sequence boundary (Pitman and Golovchenko, 1983; Jordan and Flemings, in press) depending on the character of isostatic compensation, sediment compaction history, rate of eustatic change and changes in sediment supply. Consequently, precise synchroneity among sequence boundaries is not a necessary condition for demonstrating correlation. Instead, emphasis should be placed on evaluating facies relationships and geometry of strata within depositional sequences. Detailed "system tract" models have been developed that place these facies patterns within a eustatic reference frame (van Wagoner *et al.*, 1987: Haq *et al.*, 1987).

Step 2: Determine if regional unconformities are caused by eustatic change.

Once a list of possible eustatic events has passed the test of inter-margin correlation, the task is to evaluate the possibility that each was caused by eustatic change. This is accomplished by iterations of forward and inverse modeling. Forward modeling attempts to estimate sea-level changes from the stratigraphic record; inverse modeling convolves these estimates with a margin's subsidence history in an effort to reproduce the observed stratigraphy. The degree to which the model agrees with observations is an indication of the extent of eustatic influence. The critical test is that the eustatic event yielding the "best fit" to the observed record on one margin must be similar in age and magnitude (within reasonable limits) to "best fit" eustatic events derived from other margins.

Correlation will only substantiate the time of eustatic changes, and will not, by itself, provide information about magnitudes of these changes. For this crucial detail it is essential to integrate these findings with results from other techniques of gauging sea-level change (*e.g.*, drilling into lagoons of carbonate atolls).

Step 3: Conduct Model Sensitivity Studies

As stated previously, eustasy and tectonics are the primary controls on sequence formation. Nonetheless, the stratigraphic record is sensitive to a number of other factors whose influence and interaction are incompletely understood. Consequently, there is a great need for detailed study of packages of multiple sequences in multiple locations. These can be used in a series of modeling experiments in which isostatic compensation, sediment compaction, sediment supply, *etc.*, are varied and used to derive the sensitivity of the stratigraphic record to these processes. Ironically, application of reasonable boundary conditions to both the compaction and compensation histories may require information from times far older that the interval being investigated. For all sequences that are to be modelled, it is crucial to know 1) the rifting age of the underlying crust and 2) the porosities of strata throughout the entire sediment column overlying crystalline basement. In some instances this information will be obtainable only through the release of oil industry data.

It is critical to investigate the entire anatomy of stratigraphic sequences, *e.g.*, the shifts in facies within sequences, the timing and distribution of condensed sequences, the extent of transgressive flooding surfaces, the severity of ravinement during subaerial exposure, *etc.*, as well as dating unconformities. A transect of holes through the different parts of sedimentary sequences is absolutely essential to accomplish this objective.

Methods

A properly conducted sea-level study based on siliciclastic margins will require selection of 3 or more suitable margins, and location of 5 or more drill sites along a transect of each margin. These procedures are discussed below.

Select Appropriate Continental Margins

Numerous criteria describe the ideal margin for sea-level studies. The following outline lists eleven features that the candidate margin should have:

- Relatively simple, well understood subsidence history;
- High quality, publicly available seismic grid coverage;
- Available well data;
- Good, nearby outcrop sections;
- Laterally continuous depositional sequences that allow a transect from continental shelf to adjacent deep-sea;
- Relatively complete section of the target interval;
- Relatively high sediment input and clear sequence boundaries that can be traced laterally to conformity;
- Maximum number of sequence boundaries in the target interval;
- Stratigraphic targets within reach by the drillstring;
- High correlation/calibration potential (excellent quality biostratigraphy, magnetostratigraphy, *etc.*);
- Well-established age for the start of seafloor spreading.

Seismic grid coverage is generally adequate only in those regions that have been explored for hydrocarbons. If available, these data could provide much, if not all, of the pre-drilling seismic coverage that is needed. Unfortunately, many seismic data were collected to image deeply buried horizons, and may not be adequate for the shallow, high resolution needs of sea-level analyses. Watergun or tuned airgun arrays, processed at a minimum sampling rate of 2 msec, are required to image stratal geometry in regions with all but the highest sedimentation rates. For example, a seismic source array that produces useable signals to 60 Hz will have a primary wavelength of roughly 40 m in sediment whose velocity is 2.4 km/sec. If the lower limit to vertical resolution is a 1/8 wavelength, and sedimentation rate in these strata was 1 cm/1000 yrs., the resulting 5 m vertical acoustic resolution cannot distinguish reflectors separated by less than 0.5 m.y.

Well logs provide valuable lithologic information not available on seismic profiles. The availability of well control is especially dependent upon the petroleum industry. Ideally, completion reports, logs and cuttings should be made available for evaluation during the planning stages of a scientific drilling transect.

The collaboration of these offshore studies with onshore counterparts should be an integral part of margin studies. The modern shoreline is a transient boundary separating land- and marine-based geologists who are pursuing the same goals regarding sea-level history. Drilling transects should span the continental shelf and extend seaward to beyond the shelf-break. Results will be of interest to a very wide range of land-based geologists who previously have not been closely involved with ODP. Past isolation of marine- and land-based scientists has limited the exchange of ideas and data, and hindered the development of an integrated model for sea-level changes and their stratigraphic record. In view of the requirement for a high standard of pre-drilling surveys, data compilation and analysis, it is essential to develop close cooperation between land and marine geologists in preparing pre-transect surveys.

In addition to the broader intellectual advantages of exchange between these two groups of geologists, there are a series of advantages specific to each discipline. Marine studies stand to gain through this cooperation because land geology:

- Draws on a larger, more detailed historical database;
- Provides a greater range in age of basins and sequences;

- Is based in part on subsurface well log data that can provide very detailed information about the geometry and composition of depositional sequences;
- Provides additional stratigraphic data sets for making inter-margin comparisons; and
- Can usually yield more paleontological data across important surfaces.

Similarly, marine studies can aid land-based programs of sea-level studies because:

- Marine studies add a global perspective to basin stratigraphy;
- Biostratigraphic zones are better defined in oceanic sections;
- Marine sequences reveal a much greater bathymetric range; and
- Marine sections are more complete.

As will be described more fully in the next section, a drilling transect must straddle an entire depositional sequence, from landward of the point of maximum onlap to the point of conformity at the seaward extreme. Consequently, the target sequences on the candidate margin must not be abbreviated by subaerial erosion on the landward end nor by slope defacement on the seaward end.

Three time intervals promise to yield substantial results concerning eustatic control on the stratigraphic record. These are the Oligocene-Neogene "icehouse", the early to middle Cretaceous "hothouse", and the Paleocene-Eocene "doubthouse". It is unlikely that any one margin will be ideally suited for all three intervals, and as a result, more than three margins will probably have to be examined to complete inter-regional comparisons of all three intervals. Obviously, high accumulation rates within the target intervals are desirable to maximize seismic and chronostratigraphic resolution, and to minimize the occurrence of coalesced sequence boundaries.

Conventional techniques of global bio/magneto/isotope stratigraphy will be required at the highest resolution possible to estimate (with error bars) the ages of sequence boundaries. Absolute (geochronologic) ages may not be necessary if relative ages (*e.g.*, with respect to events such as geomagnetic reversals) provide adequate correlation among transects. However, within a depositional sequence the prime requirement will be to locate "bedding planes" (= reflecting horizons) that may approximate time lines and that can be traced across the transect.

Paleolatitude of the candidate margin(s) must be considered to maximize correlation potential between drill sites and among the several margins. High latitudes are at present undesirable because of their limited biostratigraphic correlations. Magnetic inclinations are at their lowest values in low latitudes, and consequently, unoriented cores become progressively unusable as one approaches the paleo-equator. The recently developed Formation MicroScanner (FMS) may reduce this problem by providing bedding geometry that can guide the measure of absolute core orientation.

Finally, candidate margins should have a moderate calcium carbonate content. Strontium isotope stratigraphy will provide especially good correlation potential for the icehouse interval; oxygen isotope stratigraphy will be valuable for all intervals because of its power to tie margin sections to the deep sea record.

Drill Transects

The primary objective of drilling on siliciclastic margins will be to derive the age of consistently recognizable elements of a sea-level event. This will require recovery of strata juxtaposed across sequence boundaries as well as strata that represent a maximum flooding surface. A secondary objective will be to provide information useful to the estimate of magnitudes of sea-level falls. To meet these objectives, a transect of at least 5 holes (**Fig. 6**) is required as a *minimum* across any selected depositional sequence. Holes should be located to sample:

Hole 1 - The highstand coastal plain;

Hole 2 - The clinoform breakpoint on the sequence boundary;

Hole 3 - The lowest position of coastal onlap in the lowstand systems tract of the overlying sequence;

Hole 4 - The slope-fan/basin-floor fan; and

Hole 5 - The correlative conformities (in the seaward direction) of sequence boundaries.

Depositional sequences typically occur as stacked, seaward prograding packages. Consequently, a transect of five holes targeted on one sequence can also retrieve excellent information from underlying and overlying sequences. Judicious siting of a wider transect of perhaps 8-10 holes can sample several sequences.

Though sited primarily to provide information on inferred sea-level fluctuations, sequence geometry and dating of unconformities, any transect of the minimum five holes will improve understanding of the anatomy of depositional sequences, including:

- Global climatic history;
- The nature of condensed sequences/hiata;
- Shelf facies distribution;
- Shelf sediment budgets; and
- Refined resolution of correlation.

Two additional criteria underscore the need for transects of siliciclastic margins; both contain paradoxical features. 1) The continental shelf is especially sensitive to eustatic change, and is also where total tectonic history is likely to be best understood. While modeling can yield the most reliable results in this region, the length and number of hiata will undoubtedly be at a maximum. Studies in these regions will have to be balanced against those on the opposite ends of margin transects (seaward of the shelf break) where the sediment column is more complete, age-ranges of sequence boundaries are narrower, but where the subsidence history is known with less confidence. 2) Cooling of the lithosphere and compaction history of the sediment column are two of the many features critical to understanding eustatic control of the sedimentary record. Thus, even if the time interval being examined for eustatic control is contained in only a fraction of the entire sedimentary column, it is still necessary to have an accurate understanding of cooling and compaction histories over much longer time intervals, often back to the time of rifting.

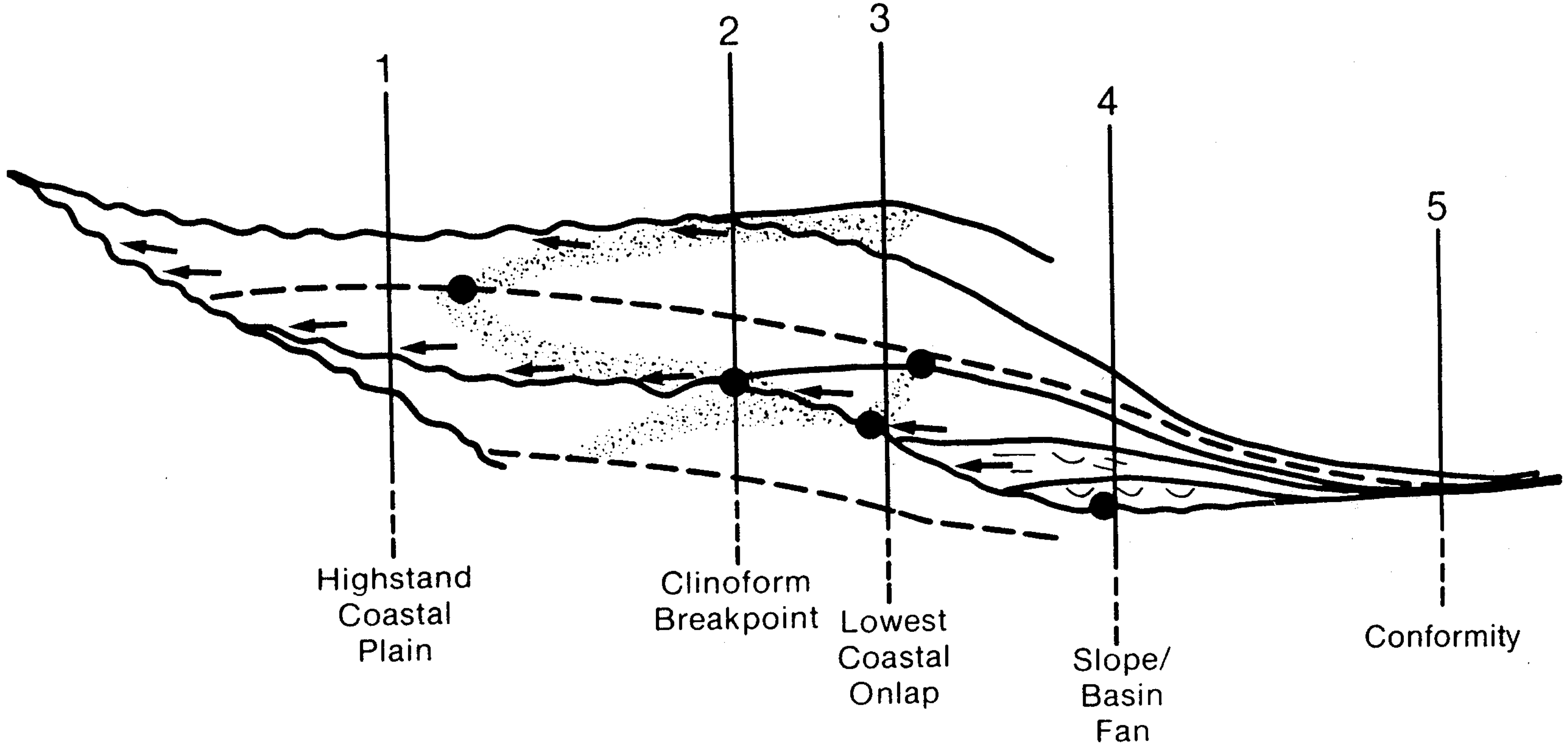

Figure 6. Schematic systems tract showing locations of recommended transect holes for siliciclastic margins.

Differentiating between tectonic and eustatic influences has historically been a difficult task. To overcome this obstacle, it is necessary to have subsidence information over a longer interval than that being investigated for sea level. While commercial boreholes can help fill this need, uncertainties in determining the long-term subsidence (loading, compaction, *etc.*) are of the same magnitude as the eustatic signal under investigation. One-dimensional backstripping does not have the resolution to determine sea-level magnitudes precisely, and it will be critical to use transects in which the ratio of tectonic subsidence and eustasy are continually varying. Only this level of sophistication in modeling can produce the lateral shifts in deposition that are expressed as sequences.

High-quality site surveying and careful selection of drillsite locations is pointless without a commensurate level of effort devoted to core recovery and analysis. Several technological considerations must be adhered to as described below.

- Vessel - Some sequences within each of the three target intervals lie beneath the inner portions of continental shelves, where water depths are considerably less than 100 m. Because the **JOIDES Resolution** must maintain position to within 3% of water depth (*i.e.*, no more than 3 m of lateral offset in 100 m water depth), it may be necessary to anchor the vessel, or to use other drilling platforms to obtain the shallowest parts of some transects.

- Casing - Young sediments beneath continental shelves are generally poorly consolidated, and to ensure the highest level of core recovery possible, methods of improving hole stability must be investigated. There may be a general requirement for casing, which will limit the types of downhole logging possible.

- Core recovery - A drilling program targeted at sea-level change has especially stringent requirements for core recovery. Drilling targets will include loosely consolidated sand plus interbedded lithified carbonates/soft sediments; core recovery of these lithologies has in the past been notoriously poor. The design of better recovery tools for these lithologies is clearly a high priority item. A rubber sleeve, commonly used by industry, has the potential to greatly improve recovery; several industry participants in the workshop noted that commercial drilling operations routinely recover unconsolidated and interbedded hard/soft lithologies with far better results than has been accomplished by the scientific community.

- Logging - A full suite of downhole logs will be required at each hole. New tools, such as the High Resolution Dipmeter, the Formation Microscanner and Digital Total Waveform Sonic will be critically important for defining features within depositional sequences and making it possible to correlate these features to other sequences.

Condensed beds associated with maximum flooding surfaces, as well as sequence boundaries, will require particularly careful analysis. We have as yet little insight into the diagenetic character, distinctive features and stratigraphic significance of these stratal surfaces, despite their importance to modeling stratigraphic and basinal history. Condensed beds are seismically conspicuous, and once they have been adequately characterized in a drillhole transect, they may be especially valuable for basin-wide extrapolation.

Unequivocal ties to seismic data are required, and can be best achieved, by several uphole seismic experiments. Other techniques are also of value: 1) Synthetic seismograms demonstrate lithologic/seismic correlation, provided the waveform of the seismic source is known. 2) Acoustic logging tools for velocity and density yield valuable measurements, but generally are degraded by high porosities in unconsolidated sediments. 3) Impedance logs derived from mathematical transformation of other log measurements (gamma ray, caliper, resistivity, *etc.*) may offer improvements over the porosity and acoustic tools, which are more sensitive to hole environment.

In general, integrated analysis of all log measurements in clustering or multivariate schemes can provide log signatures for various sedimentary attributes, *e.g.*, lithology, depositional environment or diagenetic characteristics. These will be of even greater value if coupled with shipboard natural gamma ray scans of cores to provide accurate ties to inhole log measurements.

WORKING GROUP 3

CARBONATE MARGINS, PLATFORMS, ATOLLS AND GUYOTS

Introduction

Carbonate sediments offer an excellent chance of obtaining reliable, quantitative data on short-period (<2 m.y.) amplitudes of Cenozoic and Cretaceous sea-level changes. Carbonate secreting organisms grow mainly within a few meters of the sea surface; carbonate rocks are widely distributed in the Pacific Ocean, an area with few clastic sequences suitable for sea-level studies; carbonate sequences encode isotopic information usually absent in clastic sediments; and carbonate sections are typically more continuous than clastic sequences. These considerations indicate that investigation of carbonate sediments on margins, platforms, atolls and guyots should receive high priority in ODP drilling.

The potential for determining ages with accuracies of ±0.1 m.y. is a strong argument for focusing on carbonate rocks for the study of sea-level changes. Carbonate sediments are generally rich in skeletal remains that provide a basis for biostratigraphy. Recent improvements in dating through the integration of biostratigraphy, magnetostratigraphy, isotope stratigraphy, cyclostratigraphy and laser fusion (see WG-1 report) have made further improvement possible. Development of multiple biostratigraphic zonation schemes for the Cenozoic and their integration into a numerically calibrated geomagnetic polarity time scale has provided the framework for precise dating (COSOD-II, 1987). Isotope stratigraphy based on $^{87}Sr/^{86}Sr$, $\delta^{18}O$ and $\delta^{13}C$ variations has been shown capable of improving accuracy of dating. Cyclostratigraphy, or the study of Milankovich cycles, has the potential in some cases of correlation accuracies of about 20 k.y. Where volcanic minerals are enclosed within the carbonate rocks, extremely high accuracies may be possible via laser fusion $^{40}Ar/^{39}Ar$ dating. The potential for integration of the multiple-age-dating methods is particularly well-suited to carbonate sediments (Ruddiman, Sarnthein, *et al.*, 1988).

Determining not only the timing of sea-level falls but also their amplitudes is possible where relief on a platform, such as on an atoll, exceeds the amplitude of the fall. This is possible where subsidence rates are rapid relative to the timing and amplitude of sea-level changes, and exposure surfaces are separated by unaltered strata. Where subsidence rates are slow, multiple events overprint and blur sea-level history.

Studies of carbonate rocks help overcome the provinciality of contemporary sea-level studies, the overwhelming majority of which have been done on circum-North Atlantic margins. With the exception of Australia, comparatively little work has been reported from the South Atlantic, Indian and Pacific Oceans. This provinciality largely reflects the relative lack of drilling for hydrocarbons in these areas, especially in the deep oceanic realms. Nonetheless, platform carbonate sediments are common in low latitudes, from about 25°N-25°S, in open ocean environments such as atolls and guyots, and along both passive and active continental margins. Furthermore, carbonate sediments on atolls and guyots provide sites in the Central and Western Pacific and in the Indian Ocean outside normal hydrocarbon provinces, sites which are necessary to verify and calibrate global sea-level events.

Because carbonate sequences tend to be more continuous than clastic sequences, they better encode the record of sea-level fluctuations. Unconsolidated clastics are easily eroded by bottom currents and, as a result, significant fractions may be missing from marine sections. In contrast, the tendency of carbonates to cement at early stages in their development minimizes mechanical erosion and resultant hiata.

Perhaps most importantly, carbonate-secreting organisms such as reefs form and grow in the photic zone. On carbonate platforms, the carbonate is mainly the product of photosynthesis: it is "fossil sunshine". Carbonate production is thus most intensive in the surface layer of the ocean, with the consequence that platforms tend to maintain a flattish top near the sea surface. The upward growth potential of platform organisms is greatest in low latitudes, where the water is warm and well-lighted; at higher latitudes, platform communities grow upward more slowly. The light dependence of carbonate production limits growth to the upper 75-100 m of water (most species live within a few meters of the sea surface); submergence below this zone kills carbonate-secreting benthos. Carbonate growth rates in low latitudes are one-to-two orders of magnitude greater than maximum rates of glacially induced sea-level rise, a factor that allows carbonate platforms to maintain their near-surface position (Schlager, 1981). In contrast, the response of clastic sedimentation to changing sea level is much slower than known rates of sea-level rise with the result that clastic sediments are generally less accurate paleobathymetric indicators.

Subsiding carbonate platforms are sensitive monitors of relative sea-level fluctuations. Because carbonate platforms tend to maintain themselves very close to sea level, even small drops of sea level can be recognized in cores by a suite of distinctive features (*e.g.*, karst surfaces, red solids, caliche, *etc.*, Ludwig *et al.*, 1988). In some examples, meteoric-water diagenesis may dissolve marine carbonates and deposit cement with characteristic stable-isotopic values. Platforms also record lowstands of sea level as a series of paleo-water tables encoded in the geometry and isotopic composition of cements. In contrast, periods of relative sea-level rise may be marked by distinctive clinoform patterns on seismic reflection profiles.

In summary, one can do with carbonates most of what can be done with clastics -- and a great deal more. It has been said without too much hyperbole that carbonates are the dipsticks of the ocean (COSOD-II, 1987).

Carbonate Platforms and Sea Level

Oceanic Atolls and Guyots

Oceanic atolls are carbonate caps built upon subsiding volcanic edifices. These caps initially developed as fringing reefs ringing active volcanoes. Carbonate guyots are drowned atolls where deposition failed to keep up with subsidence. While the "tectonic" (*i.e.*, thermal) subsidence history of an oceanic atoll is usually simple and predictable, the recorded subsidence history is a combination of tectonic subsidence and eustatic sea-level fluctuations. The active reef maintains a position at or just below sea level and is therefore extremely sensitive to sea-level change. Sea-level lowstands are recorded largely as subaerial exposure surfaces and diagenetic zones that typically have distinctive seismic reflection, petrologic and stable isotopic signatures. Sea-level highstands are recorded between subaerial exposure surfaces. Highstand signatures vary depending on the amount of subsequent subaerial erosion. Recent advances in shallow-water biostratigraphy, largely based on ostracods and benthic foraminifers, magnetostratigraphy and strontium-isotope stratigraphy, enable reasonable dating of atoll carbonates, especially in the Neogene (where precision is better than ±0.5 m.y.).

Suggested drilling targets to document sea-level changes are active atolls for the Neogene; and Enewetak (Wardlaw, 1987) and Johnston Atoll in the Pacific and several atolls in the Maldive chain (Indian Ocean) for part of the Paleogene. Drowned barrier reefs in the Japanese Group between 30°N and 35°N and drowned atolls of the Mid-Pacific Mountains east of Wake Island between 20°N and 25°N (**Fig. 7**) should provide a near-continuous succession of tropical reef, backreef and lagoonal environments recording sea-level fluctuations in the deep, open Pacific Ocean from early to mid-Cretaceous time half-way around the world from the circum-Atlantic and West Tethyan seaways.

These sediments comprise 10-25 m.y. of deposition centered in Aptian-Barremian time. Rudistid corals are datable to the stage level (*i.e.*, ±3 m.y.); lagoonal coccoliths should be datable with greater precision.

These sites are for the most part readily accessible to deep-sea drilling. Only shallow-water depths in lagoons prevent extensive activity using the **JOIDES Resolution**. Alternative drilling strategies are needed for atoll, lagoon, rim and flank sites to maximize information on amplitude and timing of fluctuations.

Marginal Platforms

Thick carbonate platforms on passive continental margins are likely to provide good, high-resolution records of sea-level fluctuations. Where the marginal platform continues seaward as a ramp, there are unique opportunities to evaluate global sea-level change in terms of both the timing and amplitude of such events. At the shallow end, environmentally sensitive deposits record relative sea-level drops in the form of diagenetic exposure surfaces. Continuous, gentle gradients into deeper waters allow evaluation of paleodepth changes using benthic microfossils. High-resolution seismic stratigraphy can link well-dated sequence boundaries at the deep-water end of the ramp to the less well-constrained sea-level record at the shallow end.

Dating and Stratigraphic Resolution

Platforms

Biostratigraphy. Stratigraphic resolution based on regional correlations of benthic foraminifers and ostracods in well-studied platform successions in the Neogene of Pacific atolls (**Fig. 8**) is about ±1-3 m.y.

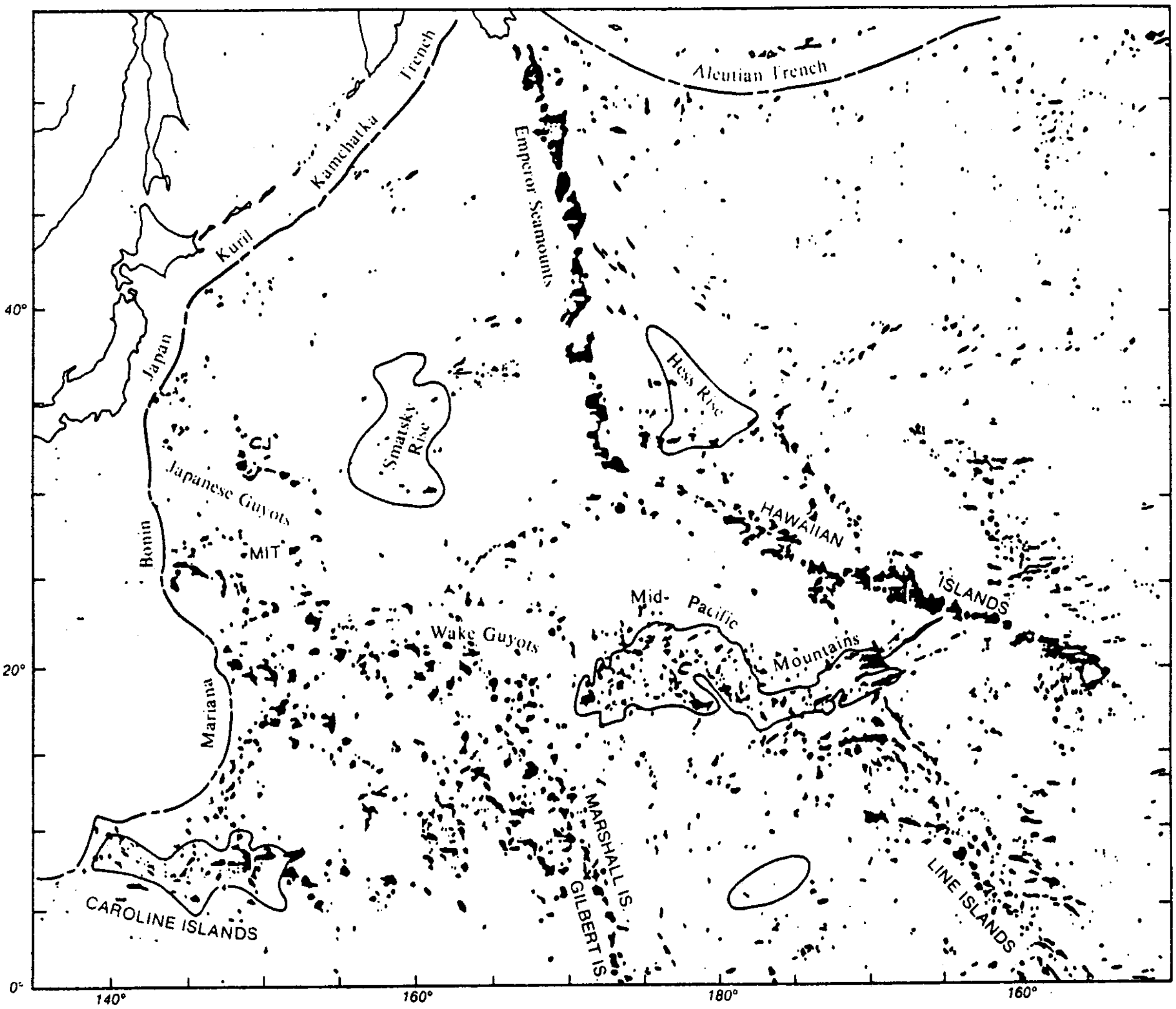

Figure 7. Seamounts in the Northwest Pacific (E.L. Winterer, pers. comm., 1989).

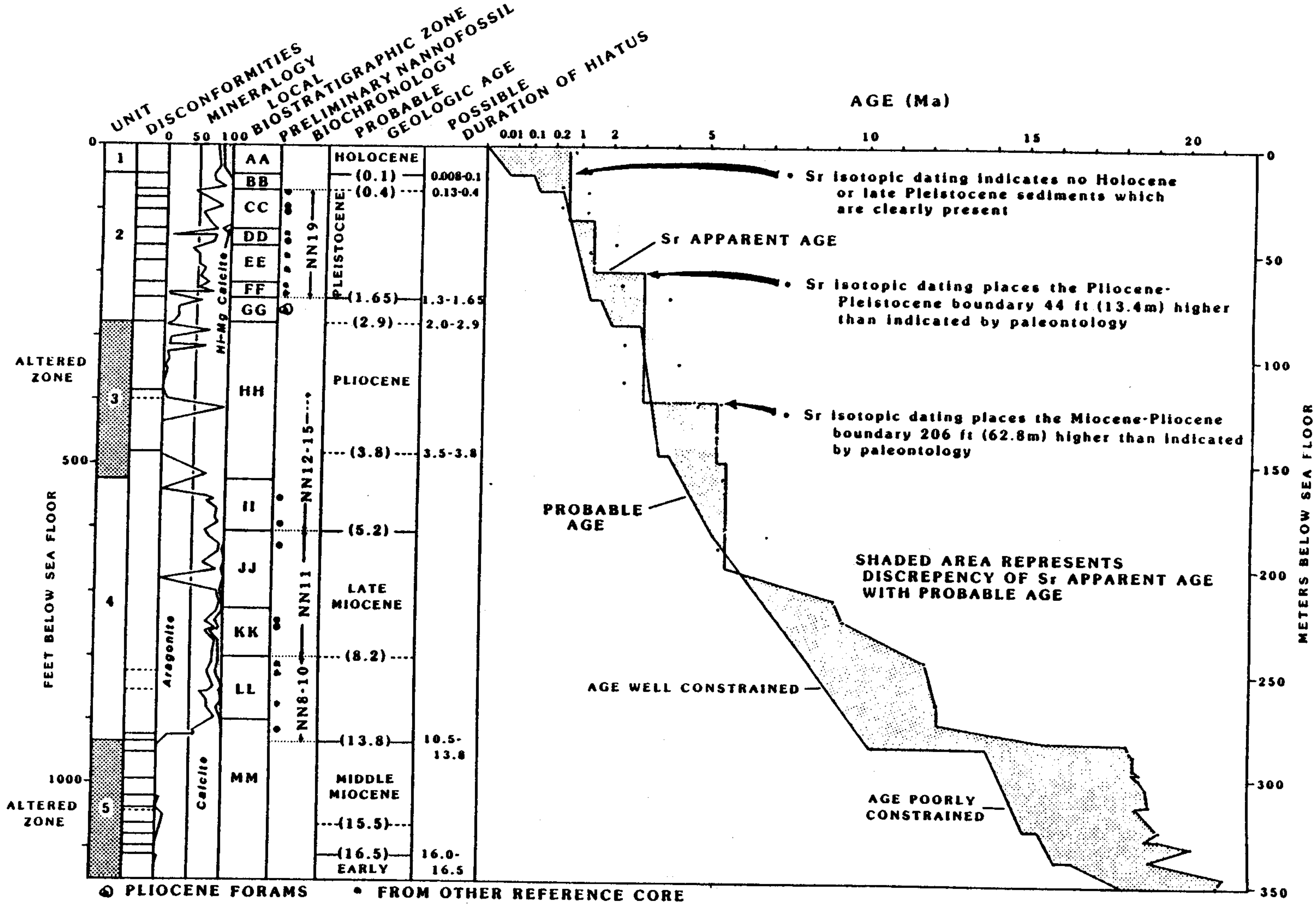

Figure 8. Comparison of geologic age and Sr apparent age from borehole KAR-1 on Enewetak Island showing geologic units, logged disconformities, mineralogy, local biostratigraphic zonation, planktic sample horizons and nannofossil zones, probable geologic age, possible hiatus duration, and probable age vs. Sr apparent age (from Wardlaw, 1989).

Work recently completed at Enewetak and Belize shows that lagoonal sediments contain nannofossils that provide stratigraphic ties between the platform and pelagic zonations. In the Bahamas, mollusc datums are also being used successfully for Neogene correlations. In Lower Cretaceous (i.e., "Urgonian") platform sediments, resolution using foraminifers, algae and rudists is about ±2-3 m.y. (R. Ginsburg, oral comm., 1988).

Magnetostratigraphy. Recent findings in Bahamian drill cores (R. Ginsburg, oral comm., 1988) show that platform carbonates, even in dolomitized sections, contain a readable record of magnetic reversals. This suggests that magnetostratigraphy can be used to date and correlate platform carbonates. To take full advantage of this technique, cores recovered from sections deposited in low paleolatitudes must be oriented.

Strontium Isotopes. Analysis of Neogene drill cores from Enewetak Atoll (Ludwig, *et al.*, 1988) shows that $^{87}Sr/^{86}Sr$ stratigraphy is probably possible. Given the problems of stratigraphic resolution in the published curve of DePaolo and Ingram (1985) and the recent refinement of the Sr-scale (J. McKenzie, oral comm., 1988), there is a good possibility that platform and deep-sea Sr records will be correlated. The step-like form of the scale (J. McKenzie, oral comm., 1988) indicates that Sr-isotope resolution is variable from one part of the column to the next. For example, strontium isotope resolution in the middle Miocene is *ca.* ±0.5 m.y., while in the late Miocene and Pliocene it is ±1 m.y. (see **Fig. 9**).

Deep Water (Off Platform)

Biostratigraphy. Well-established, detailed, low-latitude planktonic stratigraphy applies in carbonate strata on continental margins and on the deep-sea floor adjacent to atolls and guyots. Resolution varies from ±0.1 m.y. in the Plio-Pleistocene to ±0.5 m.y. for the rest of the Neogene, ±1.0 m.y. in the Paleogene, and ±1-2 m.y. in the Cretaceous.

Magnetostratigraphy. The polarity reversal sequence of the Cenozoic and uppermost Cretaceous and M-sequences of the Lower Cretaceous and the Jurassic provides the possibility of very precise global correlation at and between polarity reversals.

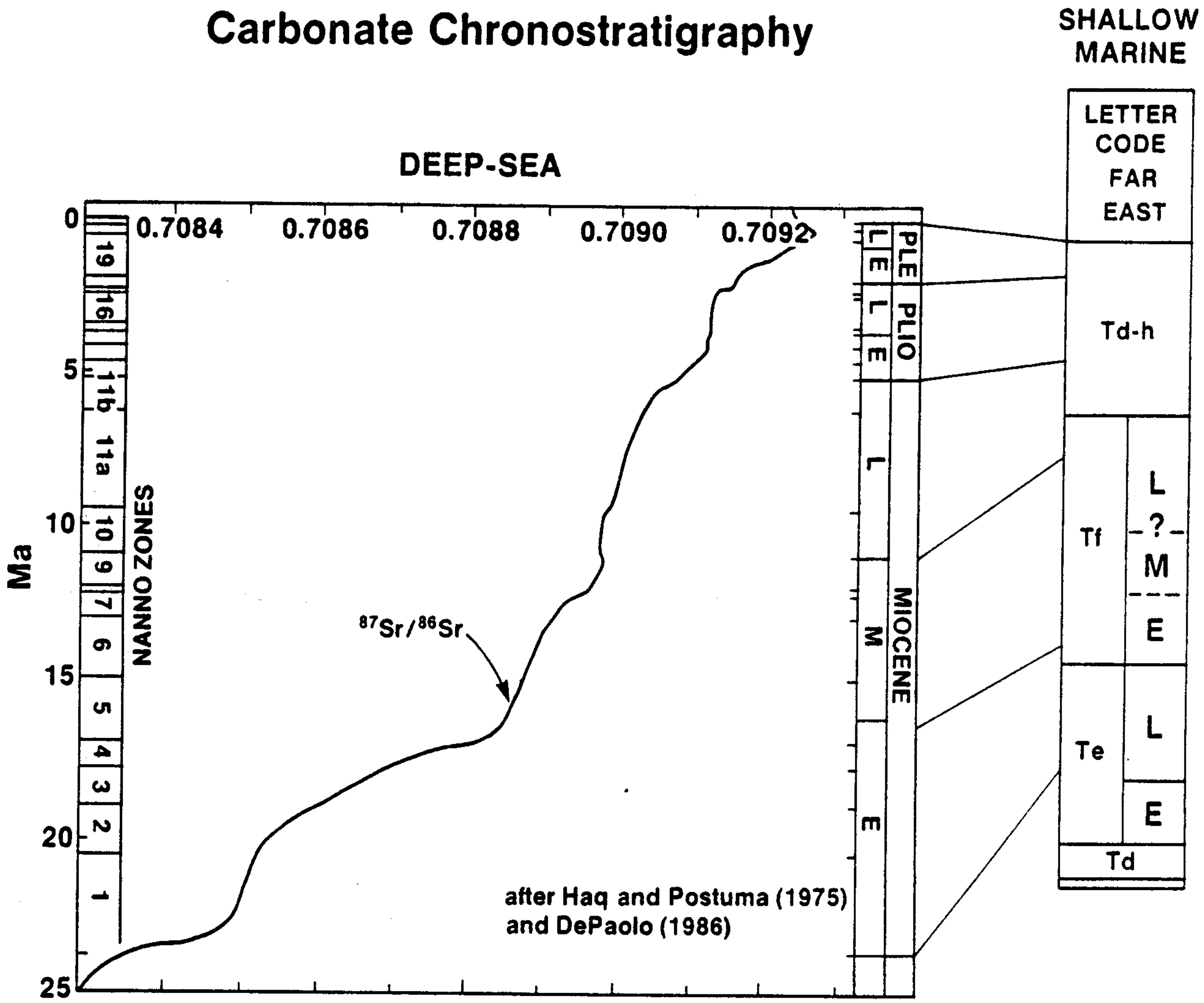

Figure 9. Comparison of deep sea vs. shallow marine carbonate chronostratigraphy (R.B. Halley, pers. comm., 1989).

Oxygen Isotopes. Seawater $\delta^{18}O$ values are preserved in diagenetically unaltered abiotic carbonates (*e.g.*, marine cements; Given and Wilkinson, 1985) and foraminifers of deep-water (off-platform) carbonate sequences. Primary seawater $\delta^{18}O$ data on deep water sediments may be used to link deep water (off-platform) sediments with high-resolution, deep-sea foraminiferal $\delta^{18}O$ records. Oxygen isotopic composition of diagenetically altered deep-water (off-platform) carbonate sediments record temporal changes in the oxygen reservoirs of rock and water which can be used to characterize the nature of the diagenetic fluids (*e.g.*, freshwater versus seawater). Identification of the oxygen isotopic signature of freshwater and subaerial exposure can be used to constrain the history of sea-level change (*e.g.*, Halley and Matthews, 1987).

Strontium Isotopes. In the Cenozoic, the Sr scale (**Fig.10**) adds another possible correlation technique. The combination of isotopes, magnetostratigraphy and biostratigraphy brings Cenozoic resolution to better than ±0.5 m.y.

Carbonate Drilling Strategies

We propose the following strategies for drilling in carbonate environments.

Marginal Platforms

- Identify a particular stratal geometry (*e.g.*, prograding clinoform) on three-dimensional grids of single- and multi-channel seismic reflection profiles and sample that geometry with transect(s) of short (*i.e.*, 400 m.) holes, *e.g.*, one hole into the correlative conformity downslope, several into bounding sequences, one into updip (*i.e.*, interpreted flooding) surfaces farther upslope.

- Complete logging, including downhole seismic experiments (*e.g.*, checkshot surveys, VSP's) for optimal time/depth conversion.

- On shallow-water carbonate platforms, use alternate drilling platforms to drill transects along available seismic control. Two kinds deserve consideration:
    - jack-up, self-propelled barges;
    - construction and/or spud barges deployed by tug.

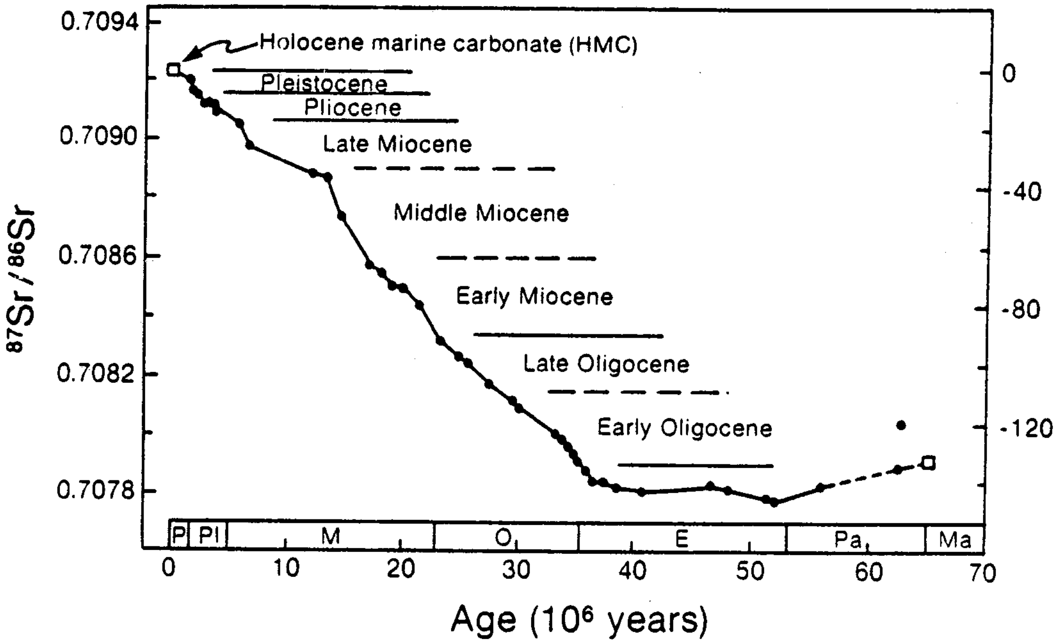

Figure 10. $^{87}Sr/^{86}Sr$ and $\delta^{87}Sr$ values of Cenozoic marine carbonate samples as a function of age (from DePaolo and Ingram, 1985).

Jack-up platforms are readily available in various centers of petroleum exploration and development. Estimated daily drilling costs are presently 20-30% of those incurred by using the **JOIDES Resolution**. Large construction barges can be adapted for drilling, including adding trailers for living quarters and a laboratory for processing cores. Such a barge, with a draft of 1 m or less, can be grounded on reef tracts or shoals and stabilized with sea water ballast. This procedure has already been used successfully to drill 100 m holes in Belize (R.N. Ginsburg, pers. comm, 1988). Estimated costs for for barge, drilling and tug are $5,000/day depending upon location.

As a recent example of the success of these systems, recoveries of 75% and better have been achieved using wireline coring systems and stepped, diamond bits in the Bahamas (R.N. Ginsburg, pers. comm, 1988).

Atolls and Guyots

Drill one or more holes at the following sites:

- In lagoons;
- On atoll and guyot rims; and
- On flanks of edifices.

Alternate platforms will probably be required to drill lagoon and rim sites. Jack-up, self-propelled barges and tug-towed construction and/or spud barges similar to those noted above for drilling on shallow water platforms are suggested. Detailed, high-resolution seismic reflection surveys will be necessary to site drill holes.

CONCLUSIONS

This section summarizes the principal scientific objectives of sea-level related drilling, identifies target time intervals that can contribute most effectively to our understanding of the problem of sea-level change, reviews programmatic and technological requirements of the recommended program and concludes with a recommended drilling strategy.

Potential locales, sites and transects suggested by participants are reviewed in Appendix III.

Principal Objectives

Workshop participants concluded that the principal objectives of the near-term drilling program should be the following:

- **Determine the synchroneity of globally correlative sequence boundaries.** This involves determining ages of events with the highest possible accuracies. In the Tertiary, accuracies of age determination of ±0.5 m.y. or better can be obtained; in much of the Cretaceous, ±2.0 m.y. may be the best obtainable by conventional biostratigraphic methods. Combining biostratigraphy with magnetostratigraphy, isotope stratigraphy and log cyclicity should provide significant improvements within the next five-to-ten years.

- **Determine whether or not globally synchronous unconformities are in fact caused by sea-level changes** or are caused by climatic changes, circulation changes, changes in sediment flux, *etc.*

- **Determine amplitudes of global sea-level changes with an accuracy of 1-5 meters.** Considerable confusion exists regarding reliability of amplitudes determined from coastal onlap and offlap studies. Drilling can address this issue through direct sampling. The best amplitude values can probably be determined from oceanic carbonate platforms such as atolls and guyots and from carbonate margins.

- **Determine rates of change of inferred events.** There is evidence from sequence stratigraphy that rises and falls are relatively rapid, but this assertion is poorly tested. Determining rates of change is critical to our understanding of the mechanisms responsible for global sea-level change.

- **Establish interrelationships between sea-level changes, climate, ocean circulation, ocean chemistry, and other environmental phenomena.**

The above objectives can be attained by:

- Recognition of effects of sea level and other forms of global change recorded in deep-sea sediments at a number of geographically separated locales;
- Analysis of stratigraphic sequences in both siliciclastic and carbonate clastic rocks on passive margins of the world; and
- Study of the diagenetic record of sea-level changes imprinted on carbonate oceanic and continental margin platforms.

Studies of oceanic carbonate platforms, carbonate margins and siliciclastic margins complement each other. Carbonate platforms and margins are probably better for amplitude determination, whereas clastic margin sequences are probably better for determination of synchroneity and rates of change.

In the wider theater of science, deep-sea data may ultimately prove to be the most valuable, for it is from the deep ocean basins that the best data will be obtained concerning linkages between sea-level changes and chemical and other proxies for ocean currents, paleoclimate, paleoceanography and paleocean chemistry. Deep-ocean sediments do not appear to be useful for measuring sea-level amplitudes, rates of change or synchroneity of unconformities, but they are valuable repositories of essential clues to the effects of sea-level change.

Targeted Time Intervals

The workshop participants believe future drilling should target specific time intervals. This is because the total number of inferred sea-level changes far exceeds the capability of the **JOIDES Resolution** to investigate more than a small number within a realistic time frame. Furthermore, the three intervals chosen represent times of contrasting global climate during which magnitudes, frequencies and rates of climatically-influenced eustatic change should be different and resolvable. Toward this end, the participants conclude that investigation of a minimum of three intervals is necessary. These are:

Neogene "Icehouse" Earth

- ***Late Oligocene-Middle Miocene.*** Biochronozones P21-N15 (Blow, 1969), polarity zones 10-5C, 32-9 Ma (Haq *et al*, 1987).

  There is compelling evidence for major glaciation throughout this interval. Eustatic signals should be resolvable and globally correlatable. These glacial signals can be compared in deep ocean carbonate plateau and continental margin stratigraphic sequences. Dating can be further strengthened by comparing stratigraphic and carbonate diagenetic markers with oxygen isotope markers at the beginning and end of the glacial cycles. These are presumed to coincide with the beginning and end of the sea-level fall.

  This interval has high and low relative sea levels known from land geology, it spans widely correlative deep-sea reflection horizons, rapid change in $^{87}Sr/^{86}Sr$ of ocean waters indicates high reliability of Sr-based studies, and the interval includes significant $\delta^{13}C$ excursions. Bio- and magnetostratigraphic resolution are high. This time interval includes events that could cause global sea-level change as diverse as the desiccation of the Red Sea, the entrance of the Gulf Stream into the Norwegian-Greenland seas, and buildup of ice in Antarctica.

  Investigation of this interval will also permit us to assess relative amplitudes of eustatic and local pulses of sea level change. The glacial component of the signal should be truly eustatic and present at all sites, whereas local effects from sedimentation, compaction, local tectonics, *etc.* will be restricted to specific sites, and should be separable from the eustatic signal if sea-level amplitudes are determined at enough sites. This will give us an estimate of the magnitude of local effects, a value for which we have little data at the present time.

Cretaceous "Hothouse" Earth

- *Aptian-Coniacian.* Biochronozones LC8-UC7 (van Hinte, 1976); polarity zones MO-long normal polarity zone 34, 116-87 Ma (Haq *et al.*, 1987).

  The Aptian-Albian subinterval includes a widely observed sea-level fall of large amplitude thought to be global in nature. Sampling this event on a global basis will be an important test of synchroneity, amplitude and rates of change at a time when glaciation is thought unimportant. The biostratigraphic accuracy with which synchroneity can be determined for this event is approximately ±2.0 m.y. Although the event occurs during a period of unchanging magnetic polarity, it is close enough to Cretaceous polarity changes for its determination to benefit from the proximity of a magnetic polarity reversal. Thus, improvement in accuracy of timing can be obtained by extrapolation of sediment accumulation rates from a nearby polarity change.

  Carbonate caps on a number of guyots in the central Pacific were formed during the Aptian-Albian subinterval, and provide important geographic markers for testing and determining sea-level change parameters at this time.

  During periods of highstand flooding in the Cenomanian-Coniacian subinterval, the Mediterranean and Atlantic were intermittently connected by a shallow sea over the African continent . Biostratigraphic resolution is excellent. The Global Sedimentary Geology Program has selected this period of "ultra-thermal earth," a time characterized by the accumulation of thick black shales, as its first subject of international study on land.

Paleogene "Doubthouse" Earth

- *Latest Paleocene-Middle Eocene .* Biochronozones P5-P10 (Blow, 1979); polarity zones 25-21, 55-48 Ma (Haq *et al.*, 1987).

  This interval covers at least two widely recognized, unconformity-generating events at approximately 55 and 49 Ma. Bio- and magnetostratigraphic resolution have excellent potential, but recovery problems may arise in the deep sea because of the common occurrence of cherts (these cherts are of possibly global environmental significance). The Himalayan collision began during this interval. Thus, investigation of this interval provides an opportunity to observe the effect of the Himalayan collision on ocean and atmospheric circulation, and an opportunity to examine the complex linkage between lithosphere, hydrosphere and atmosphere, and their impact on eustatic change.

"Doubthouse" time is non-glacial to some but glacial to others; study of this interval would test that controversy. Sea-level excursions include widely observed, high-amplitude events during periods of no known glaciation. Their investigation serves to evaluate synchroneity, to measure amplitudes and rates and to test their similarity with both non-glacial and glacial events. Since these events occur during periods of relatively frequent magnetic polarity changes, they can be dated with an accuracy of ±0.5 m.y. or better.

We anticipate that transects of three to six margins in addition to holes on oceanic plateaus will be required to obtain the geographic and geological diversity necessary to test convincingly the hypothesis of global sea-level changes. Sites will require good documentation in the form of multiple seismic lines or grids coupled with data from wells sufficiently close to be extrapolated with confidence to areas of interest. Sites and transects will be required in low-latitudes where biostratigraphic resolution is good but magnetostratigraphic resolution is poor, and in mid-to-high latitudes where biostratigraphic data are less reliable but magnetostratigraphic resolution is better. Oriented cores will greatly improve magnetostratigraphic resolution at low-latitude sites.

Programmatic and Technological Requirements

The workshop identified a number of programmatic and technical issues that merit discussion.

The first is the need for alternate drilling platforms or possibly anchored drillship operations. This will be necessary both to characterize adequately the Neogene interval, or indeed, any Neogene target, and to determine the amplitudes of the eustatic events on atolls. There appears to be no choice in the matter. The data from atolls are critical and not obtainable elsewhere, and the water is too shallow over Neogene atolls and carbonate banks to permit conventional **JOIDES Resolution** drilling.

The second item is the need for intensive, complementary studies of land geology in areas with good exposures of targeted intervals. Land and marine investigations each contribute uniquely to the understanding of sea-level phenomena. Marine data provide an excellent overview of the total sequence geometry through seismic imagery, typically have more nearly complete sections, superior biostratigraphic control, and provide the opportunity to select the specific part of the sequence to be sampled. Land data, on the other hand, allow for more continuous sampling along a sequence boundary, and provide stratigraphic details unobtainable from a limited number of cores taken during an ocean drilling program.

Certain technological improvements are also necessary.

- First, we require far higher recovery rates in carbonate sequences than are currently obtained. We believe this can be done. Fixed platform drilling of shallow carbonate banks has routinely recovered in excess of 80% of cores penetrated in contrast to about 10% averaged by the **JOIDES Resolution.**

- We also require recovery of unconsolidated clastic sediments. Industry recovers a high percentage of unconsolidated sediments using a rubber sleeve liner in the core barrel. It should be possible to modify this technology for use by the **JOIDES Resolution.**

  Failure to do either of the above will seriously impair the investigations of sea-level changes because both carbonates and unconsolidated clastic sediments will make up a high percentage of the sediments being investigated.

- High-resolution age determination in low latitudes requires oriented cores for determining magnetostratigraphic orientation. Oriented XCB cores will also be required.

- Finally, a method is required for recovering a high percentage of a section from alternating hard and soft layers, as, for example, cherts and chalks in the deep sea.

In conclusion, we note that seismic and well data bases required for the preliminary selection of study areas are poor. Only one site was well documented at the workshop. Early correction of this problem is essential if planning is to proceed at a rate necessary for drilling on margin sites within a period of no more than 3 years. This is the minimum time required to collect the site survey information. We need a concerted effort to identify areas potentially suitable for margin transects and to obtain the necessary data (*e.g.*, from the petroleum industry).

DRILLING STRATEGY

Data available to workshop participants were not adequate to specify transect locations. Workshop participants, therefore, suggested the following drilling strategy in lieu of a drilling program.

The participants believe that the principal drilling requirements for solving sea-level problems defined previously are:

- **Three or four margin transects** of each of the 3 targeted time intervals (some transects may encompass more than one time interval);
- **Investigation of Tertiary and Cretaceous atolls and guyots**;
- **Drilling as many relevant deep-sea sites as feasible**; and
- **Wide geographic separation** of transects both in paleolatitude and paleolongitude.

To obtain adequate geographic dispersion of margin transects, we suggest 2 megatransects comprising a total of 7 legs. One megatransect should extend north-south through the Atlantic Ocean from medium-to-high northern latitudes to mid-to-high southern latitudes. The second megatransect should extend eastward from a low-latitude site in the Atlantic Ocean through the Indian Ocean and into the Pacific. The Atlantic low-latitude site can be common to both east-west and north-south megatransects.

Within the Atlantic megatransect, we suggest 4 margin drilling legs devoted to (1) a northern, high-latitude transect, (2) a northern mid-to-low latitude transect, (3) a southern mid-to-low latitude transect and (4) a low-latitude or equatorial margin transect. The east-west megatransect will consist of the previously mentioned equatorial margin transect and at least 3 other transects in the Indian Ocean and the Southeast Asia-Southwest Pacific area. We include a possible Maldive transect (Appendix III) within this megatransect. One or more legs to investigate sea-level changes on Pacific guyots and atolls will form the eastern terminus of this transect.

The two megatransects, the deep water legs and the atoll-guyot leg(s) complement one another. The Atlantic megatransect should:

- Consist mainly of rapidly deposited clastic sections that provide good temporal resolution;
- Provide better paleomagnetic dating because of greater inclination of the magnetic field at higher latitudes; and
- Provide paleo-surface water temperatures that are more sensitive to global climactic changes.

Results from the Atlantic megatransect will be readily integrable into the abundant literature on seismic sequence stratigraphy of Atlantic margins. The east-west megatransect, on the other hand, will consist mostly of transects across carbonate margins. Data from these transects will provide better:

- Resolution of amplitudes of sea-level excursions;
- Biostratigraphy;
- Overall dating of events; and
- Climatic and chemical proxy information.

The Formation MicroScanner (FMS) recently installed on the **JOIDES Resolution** will help determine orientation of cores from low latitudes and hopefully lead to a significant improvement in paleopole information from low-latitude sites.

Drilling along the proposed megatransects will provide geographical diversity necessary to assess the global synchroneity of sea-level events. Comparison of data from widely separated sites in different parts of the world should allow separation of the local, regional and global components of sea-level change. Multi-method dating (biostratigraphy, paleomagnetics, isotope geochemistry, laser fusion) can provide age resolution sufficient to determine rates of change of sea-level related parameters.

The integration of deep-sea and transect data will provide important information about the linkages between global climate, sea-level change, variations in ocean chemistry and other, possibly unsuspected, environmental parameters.

In summary, we believe that the proposed strategy represents an optimum solution to the challenge of investigating an important global problem through scientific ocean drilling.

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	Steering Committee	Session Chairs	Editorial Committee
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P. Vail	X		
J. van Hinte	X	X	X
B. Wardlaw			X
E. Winterer	X	X	X

Peter Vail led a pre-workshop field trip to the Guadalupe Mountains near El Paso to examine evidence of sea-level changes in the Permian section of West Texas. (See cover photo.) Special thanks to Debbie Waits of the Geophysics Department at Texas A&M University for her help in typing and editing this report.

A list of attendees is provided in Appendix I.

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WORKSHOP ATTENDEES

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APPENDIX II

WORKSHOP AGENDA

THE ROLE OF ODP DRILLING IN THE INVESTIGATION OF GLOBAL SEA LEVEL

October 24-26, 1988
El Paso, Texas

Monday

Morning session 8:45 - 12:15
- Welcoming remarks (Watkins) 8:45 - 9:00
  - Workshop logistics, origin, organization and desired products
- Announcements or summaries of related symposia 9:00 - 9:30
  - Ocean Sciences Board conference on Continental Margins (Austin)
  - Global Sedimentary Geology Program (Ginsburg)
  - ComFan II (Bouma)
  - US-Soviet Stratigraphic Program (Berggren)
  - Chapman Conference on long-term sea level changes (Sahagian)
  - COSOD II (Mountain)
- Keynote talks: "Sea Level Records Provided by Drilling" 9:30 - 12:15
  (15 min talk + 15 min discussion each; van Hinte, moderator)
  - Exposure Surfaces in Atolls (Winterer)
  - Stratigraphy of Carbonate Platforms and Margins (Eberli)
  - coffee break 10:30 - 10:45
  - Stratigraphy of Passive Margins (Christie-Blick)
  - Stratigraphy of Active Margins (von Huene)
  - Oxygen Isotopic Indicators of Ice-Volume Change (Miller)

Lunch 12:15 - 1:30

Afternoon session 1:30 - 5:10 PM
- Accompanying technologies:
  - "Their Use, Misuse, + Future Improvements" 1:30 - 3:10
    (15 min talk + 5 min discussion each; Tucholke, moderator)
  - Chronostratigraphic Resolution (Berggren)
  - Seismic Resolution (Austin)
  - Drill Core Recovery of the *Resolution* (O'Connell)
  - Logging Aboard the *Resolution* (Golovchenko)
  - Subsidence Modeling (Steckler)
- Short talk grab-bag 3:10 - 3:40
  - Anybody, any subject
  - Maximum 3 minutes, 1 slide/overhead each
  - coffee break 3:40 - 4:00
- Open discussion (Mayer, moderator) 4:00 - 5:00
- Working group structure (Mountain) 5:00 - 5:10
  - Titles
    - "Deep Sea" (Mayer + van Hinte, chairpersons)
    - "Clastic Margins" (Tucholke + Christie-Blick, chairpersons)
    - "Carbonate Margins, Platforms + Atolls" (Austin + Winterer, chairs)

Common mandate
    Define critical questions, identify available data
    Determine gaps in both data and technologies
    Develop strategies for closing gaps + answering critical questions

Dinner 6 - 8 PM

Evening session 8 - 10 PM
"Results of ODP Leg 122 - NW Australian Margin" (O'Connell; 30 mins)
General topic posters, data displays + beer

Tuesday

Morning session 9 - 12
Working groups in four parallel sessions
    Mix of posters/talks/open discussions determined by chairpersons

Lunch 12:00 - 1:30

Afternoon session 1:30 - rest of day/evening
Preliminary WG reports to entire group (Mountain, moderator) 1:30 - 2:10
Return to parallel working group sessions 2:10 - rest of day/evening

Wednesday

Morning session 9 - 12
Continue four parallel working group sessions
    Derive short, written working group conclusions

Lunch 12:00 - 1:30

Afternoon session 1:30 - 5:00 PM
Reports by working group chairpersons 1:30 - 2:30
    Consensus of working group mandates
Group discussion (Watkins + Mountain, moderators) 2:30 - 4:45
    Prioritize list of future drilling studies of sea level
    Identify data gaps
    Identify specific demands on ancillary technologies
Closing remarks (Watkins) 4:45 - 5:00
    Assign individual responsibilities re: writing the report
    Set schedule for revising and distributing final report

Thursday + Friday

Sub-set of steering committee completes draft report
    Draft to be circulated among steering committee and interested attendees
    Final report to be submitted to JOI for distribution

APPENDIX III

POTENTIAL DRILLING TRANSECTS, TARGETS AND/OR LOCALES

Clastic Margins

Gulf of Mexico (Texas)

This transect would be located north of the Brazos Ridge through the Galveston offshore area and into East Breaks. Holes drilled would penetrate an excellent thickened late Miocene-Recent section. This corridor is minimally affected by faulting and diapirs. Extensive commercial seismic data is available, with numerous well logs including extensive biostratigraphic and some isotopic dating. These data will allow optimum location of the drill sites. Industry will assist in the planning of this transect. Regional structure and isopach maps are available from current mapping in the area by Texas A&M University students.

The section contains 0-1000 m of Plio-Pleistocene clastics, overlying up to 4000 m of Miocene sediment. The seismic data reveals numerous downlapping reflectors which define sequences and condensed sections. Although this is a region of active hydrocarbon production, safety can be assured by twinning several of the many dry holes in the area. The Oligocene section is too deep to be reached by ODP drilling. Neogene stratigraphy is well established in the Gulf, permitting basin-wide correlations and aiding the dating of major seismic reflectors.

The combination of Plio-Pleistocene and Miocene sediments is unique and can readily be compared with existing global studies. The available data framework for the late Pleistocene will allow a comparison with the Pliocene, leading to a better understanding of changes throughout the middle and late Neogene. This transect can provide excellent data from part of the icehouse interval.

Gulf of Mexico (Alabama)

This transect would begin nearshore east of Mobile Bay and extend southwest towards De Soto Canyon. The main objective would be to sample a complete set of prograding Miocene sequences. Holes drilled 1500 m would penetrate to the Oligocene, identifiable by a good faunal marker. Commercial seismic grids are extensive and of good quality. Numerous well logs with biostratigraphic data are available.

The section comprises a prograding clastic sequence of Appalachian provenance, and extends across a stable platform. Seismic lines show numerous clinoform features, including sequence boundaries. Some gas sands occur in the section, but are easily identified as bright spots and thereby avoided. An excellent Miocene biostratigraphic reference is available for the Gulf Coast and Gulf of Mexico.

The strengths of this corridor are:

- Extensive data base available;
- Industry participation virtually assured; and
- Complete Miocene section (cf. other transects)

Mid-Atlantic USA

The eastern margin of the United States rifted from Africa at roughly 175 Ma, and has experienced a relatively uniform cooling history since that time. The unsuccessful exploration for hydrocarbons during the last decade provided two benefits for future sea-level studies along the mid-Atlantic margin:

- A substantial body of seismic data, well logs and general stratigraphic information is available; and
- Safety concerns for scientific drilling are minimal.

The disappointing elements of this potentially valuable library of information are:

- Vertical resolution of the small amount of released seismic data is marginal for sea-level studies;
- Little information was retrieved from the upper several hundred meters of section because of casing requirements in exploration wells; and
- The vast majority of drilled section was not cored, so that chronostratigraphic control required for sea-level studies cannot rest on this data set alone.

But in terms of framing the major targets, these, along with the numerous wells onshore in the coastal plain, represent a strong positive feature to this margin. Furthermore, Miocene outcrops are well known in the coastal plain.

Transects of the eastern US margin would cover in their entirety both the icehouse and hothouse intervals. The doubthouse section, though present, is both thin and abbreviated on its landward side -- the position of maximum coastal onlap occurred west of the present coastal plain, and has since been eroded. Despite the comparatively slow thermal subsidence of the margin nearly 150 m.y. after rifting, sediment supply rates during the "ice house" interval were very high, and a number of base level changes (sequence boundaries) during this interval can be seen on available seismic data. The icehouse interval is within reach of present ODP drilling, roughly 100 to 1200 m subbottom. The hothouse section, however, is buried by as much as 3 km.

South Australia

The South Australian margin (Eucla Basin-Great Australian Bight Basin) is particularly attractive from the point of view of post-rift tectonic stability, clearly identifiable Cenozoic sequences, and availability of good open-file industry and BMR seismic lines. Less advantageously, the Cenozoic sediment supply was low, leading to a thin and carbonate-dominated succession both onshore and offshore.

A little further east, the Otway Basin off northwest Tasmania is a related and similarly attractive target. Previous ODP site proposals exist for the continental slope here (WTM1-6; Branson, in Crook *et al.*, 1984). The nearby onland Otway Basin is also well studied, and has been interpreted in preliminary sequence terms by Partridge (1976). The Great Australian Bight has the disadvantage of a relatively thin and carbonate-dominated Cenozoic succession. Some mid-Cenozoic volcanism occurs, but a transect could be targeted to avoid these presumably local effects.

Eastern New Zealand

The eastern South Island continental margin rifted in the late Cretaceous (*ca.* 80 Ma), and has since been subjected to passive margin subsidence. Late Cretaceous through early Oligocene sequences are transgressive, followed by a regional mid-Oligocene unconformity (Marshall Paraconformity) and early Miocene through Recent clinoform regression. Apart from local Eo-Oligocene and late middle Miocene intraplate volcanism, the margin has a tectonically uncomplicated subsidence pattern. The main effect of the mid-Cenozoic to recent Alpine Fault plate boundary in western South Island has been beneficial, in that it has provided a source of abundant terrigenous detritus to feed the shelf clinoforms in the east.

Three separate potential sea-level transects exist in eastern South Island, and all are within range of present **JOIDES Resolution** drilling (*ca.* 1.5 km):

- Neogene (including mid-late Miocene) clinoform sequences;
- Oligocene Marshall Paraconformity, which coincides with regional sea-level highstand contrary to the prediction of mid-Oligocene global lowstand; and
- Paleocene-Eocene sequences, which are located at shallow depths below the seafloor along the western margin of the Great South Basin.

Important secondary ODP targets in the region include the early mid-Cenozoic inception of the Southern Ocean circulation system, and the early history of the ancient Bounty Channel deep-sea channel system.

The eastern New Zealand margin forms a particularly attractive sea-level target region because of:

- Extensive open-file seismic data;
- Excellent local biostratigraphy;
- Known basin setting;
- Active research on its sequence stratigraphy;
- Multiple sea-level targets available; and
- Site-survey vessel available (**Rapahuia**).

The main disadvantage is:

- **Shelf-edge to slope transect into the head of the Bounty Trough is into intermediate depths on thinned continental crust** and true abyssal plain lies further east at the terminus of the Bounty Channel.

Ceara (Mundau) Basin

Backstripped subsidence patterns for continental shelf wells show an exponential thermal decay pattern typical of passive continental margins commencing in the Albian (*ca.* 110 Ma). Eocene to Miocene volcanism is observed in the distal rise portions of the seismic lines.

Advantages of this basin are:

- **30,000 km of industry multifold integrated seismic lines available** in the area, including regional lines which extend from the shelf across the slope and rise. Line quality ranges from good to excellent.

- **At least 51 industry wells exist** along the continental shelf, and the continental slope is planned for drilling in 1989. However, because Ceara Basin is oil producing, the public availability of these data will have to be discussed with PETROBRAS (the state oil company of Brazil).

Disadvantages are:

- **No onland outcrop sections** exist, since the basin is entirely offshore.

The post-early Eocene section is well represented in the basin, with a documented inner shelf to bathyal paleo-bathymetry based on benthic foraminifera. Overall, the first-order stratigraphy is regressive (perhaps in sympathy with the "established global" sea-level curve of Haq *et al.* 1987), but second and perhaps third-order cycles are suggested by seismic stratigraphic analysis.

High sediment input has generally been characteristic since the middle Eocene. Sequence boundaries are therefore clearly exhibited on the seismic sections. Cycles of shallow-water carbonates and slope turbidites are also observed. The paleo-sea-level significance of this can be inferred by analogy with the Campos Basin, where the slope has been extensively drilled. The carbonate build-ups can be traced downslope into foram ooze or marl facies which are interpreted as condensed sections deposited during maximum flooding events. Turbidite sand mounds and related sediments are interpreted as Lowstand Systems Tracts, including Basin Floor Fans, Slope Fans and Lowstand Progradational Wedges.

At least 8 sequences occur within the post-early Eocene section, suggesting that sequence boundaries are present and well recorded. On the shelf, 2000 m penetration will reach the top of the early Eocene unconformity. On the slope and rise, 1500 m or less is required.

Nannofossil and planktonic foraminiferal assemblages are abundant and well tied to the international standard biozones. Magnetic stratigraphy is hampered by the equatorial position of the basin.

Beaufort Shelf

Beaufort Shelf is suggested by COSOD II as a possible site for sea-level study.

The advantages of the area are:

- Simple subsidence history;
- Good open-file well/seismic coverage; and
- High sediment flux in the Paleogene/Neogene.

Disadvantages of the area include:

- Perennial ice cover. There are consequent operational difficulties and a lack of publicly available seismic and well control;
- Lack of marine outcrops nearby on land;
- Difficult biostratigraphic correlation because of the endemic nature of Arctic flora/fauna; and
- Extensive industry cooperation will be required.

South China Sea

The South China Sea is a marginal sea formed by Oligocene rifting and Miocene to Recent rapid subsidence of a failed triple junction. Three major land masses flank the basin, each with individual potential for onland sea level study, *viz.* mainland China (to the west), Taiwan-Philippines (east) and Indonesia (south).

China is attractive as a clastic, partly deltaic, margin; Taiwan and the Philippines are deep-sea sections exposed by Cenozoic uplift; and Indonesia is a passive carbonate margin. Following initial Oligocene rifting, the three sides separated and acquired thin, upward deepening marine sections. After the triple junction failure during middle-to-late Miocene, the basin subsided by crustal cooling. The resulting sedimentary sequence is predominantly Plio-Pleistocene.

Active exploration has resulted locally in good industry seismic coverage. However, the data is either industry-proprietary or governmentally controlled, and may therefore be difficult to access. A modest amount of academic seismic data exists also, particularly off Hong Kong. Rare and inconsequential wells have been released. Outcrop sections are isolated, small in extent and poorly studied. Cooperation and/or collaboration with the People's Republic of China will be required.

Because the sections are largely marine, microfossils are abundant and typical of tropical zonations. Precise biostratigraphic correlation is therefore possible.

Proprietary studies of ARCO and Exxon in collaboration with the People's Republic of China suggest that the South China Sea margin has excellent potential for a Neogene transect. Basal early Oligocene marginal marine or continental sediments overlie Paleozoic basement, and are succeeded by thin late Oligocene and early Miocene shallow marine clastics with intermittent carbonates in the early-middle Miocene. Siltstones and shales were deposited as slope sediments during the middle Pliocene subsidence, and thick prograding clastics typify the Pleistocene to Recent. Scattered outcrops exist but are too poorly known to be properly evaluated.

Seismic profiles near the margin indicate that approximately 2 km of relatively undisturbed sequences exist through the Cenozoic. These hold promise for a relatively complete sea-level history for the region. The main difficulty appears to be a potentially significant tectonic signal superimposed on the eustatic signal.

Carbonate Margins

West Florida Carbonate Ramp

The west Florida carbonate margin is an excellent example of a carbonate ramp. It meets the general requirements put forth by COSOD-II for a passive margin setting, including:

- o Relatively well-known subsidence history;
- o High, uniform accumulation rates;
- o Drill core and seismic data available from industry;
- o On-land outcrop sections; and
- o A nearly complete stratigraphic section.

Most importantly, high-quality seismic reflection data exhibit well-developed sequences with a high degree of lateral continuity between shallow- and deep-water regions. Sea-level changes evidenced in shallow-water facies can thus be related to sequence boundaries, whose correlative conformities in deep water can be accurately dated.

Stratigraphically continuous, well-preserved Paleogene-Neogene pelagic carbonates along the west Florida slope allow development of a very high resolution chronostratigraphy (up to ±0.05 m.y. in the Plio-Pleistocene) using biostratigraphy (including palynology), magnetostratigraphy and isotope stratigraphy, as demonstrated for ODP Site 625. Furthermore, because the sea floor is well above the CCD, there is a paucity of unstable carbonate minerals, and diagenetic alteration of the deeper water facies is minimal.

Para-Maranhao Basin (Brazil)

In the Para-Maranhao basin, located just east of the Amazon Mouth Basin on the equatorial margin of Brazil, rifting began during the earliest Aptian and drifting began during the early Albian. The principal advantages of studying sea-level changes in the basin are:

- A 4 km thick carbonate platform of Paleocene to Recent age;

- Published Cretaceous and Cenozoic biostratigraphy, paleoecology, basin evolution and tectonic setting (Cainelli and deMoraes, 1986); and

- Good PETROBRAS multichannel seismic coverage and moderate well control.

The carbonate platform is mainly aggradational, with an oversteepened seaward slope affected by listric faults that displace Paleocene-Oligocene strata. Relative sea-level lowstands are suggested by the conspicuous vadose zones and karstic paleotopography. Canyon cutting during the late Oligocene resulted in bypassing of siliciclastic sediments to the continental slope followed by early Miocene canyon filling and shallow-water deposition in the mid-to-late Miocene.

The principal difficulty is:

- Difficult drilling conditions in the carbonate section because of karst and vadose zones.

Bahamas Platform

The Bahama Banks offer an opportunity to tie clear sequence stratigraphy to a shallow-water carbonate succession. There exist:

- A grid of excellent commercial multichannel seismic profiles across Great Bahama Bank (Eberli and Ginsburg, 1987);

- Three continuous, shallow (*ca.* 100m) borings which exhibit a combination of magnetic reversals and biostratigraphy, giving rates of deposition of from 15 to 50 m/m.y.; and

- Background information on facies and diagenesis from detailed study of approximately 20 continuous borings on both Great Bahama Bank and Little Bahama Bank.

The Maldives

The Maldives Archipelago is part of an enormous carbonate system on top of an elongated north-south lineament related to the northern motion of the Indian Plate over a hot spot. The island of Réunion is the present manifestation of the hot spot which produced the Island of Mauritius, the volcanic ridge underlying much of the Mascarene Plateau (Nazareth and Saya de Malha Banks), Chagos Bank, the Maldives and Laccadives Archipelagos and the massive flood basalt volcanism of the Deccan Traps, western India (Duncan *et al.*, 1988). Thick shallow reefal carbonate sequences (1-2 km in thickness) have formed on top of the slowly subsiding volcanic edifices. Current knowledge can be summarized in the following paragraphs.

- **Basaltic Basement**: Ar/Ar analyses give an age of 55-60 Ma (see **Fig. 11** for location). These early Eocene ages fall on a trend of northward increasing ages along the volcanic ridge connecting the hot spot of the Island of Réunion and the Deccan Traps, northwest of India (O'Connor and Duncan, 1984; Duncan *et al.*, 1988).

- **Shallow Carbonate Edifice of the Maldives Archipelago**: Industry (Elf) and ODP holes penetrated thick sequences of mostly shallow carbonate limestones and dolostones overlying basaltic basement (see **Figs. 11** and **12** for location).

- **Drill Holes**

  NMA (North Male Atoll 1) well: This well penetrated 2,100 m of inner neritic to outer neritic-upper bathyal limestones and dolostones, and 130 m of basaltic basement (**Figs. 11** and **12**). Oldest sedimentary rocks are early Eocene in age and age of underlying basalt is 55 Ma (Duncan, pers. comm). The lower (2,100 to 1,400 mbsl) and upper parts (top 880 m) of the sequence were deposited in an inner neritic, reefal or shoal environment, whereas the middle part (1,400 to 880 mbsl) of the sequence was deposited in deeper water (outer neritic to upper bathyal) environments (**Figs. 12** and **13**).

  ODP Site 715: (**Figs. 11** and **12**). The top 105 m penetrated a late Pleistocene and middle to early Miocene pelagic section. From 105 to 211 mbsl, the hole penetrated early Eocene shallow water limestone overlying basaltic basement (age of 55 to 60 Ma; Backmann, Duncan *et al.*, 1988, and Duncan *et al.*, 1988).

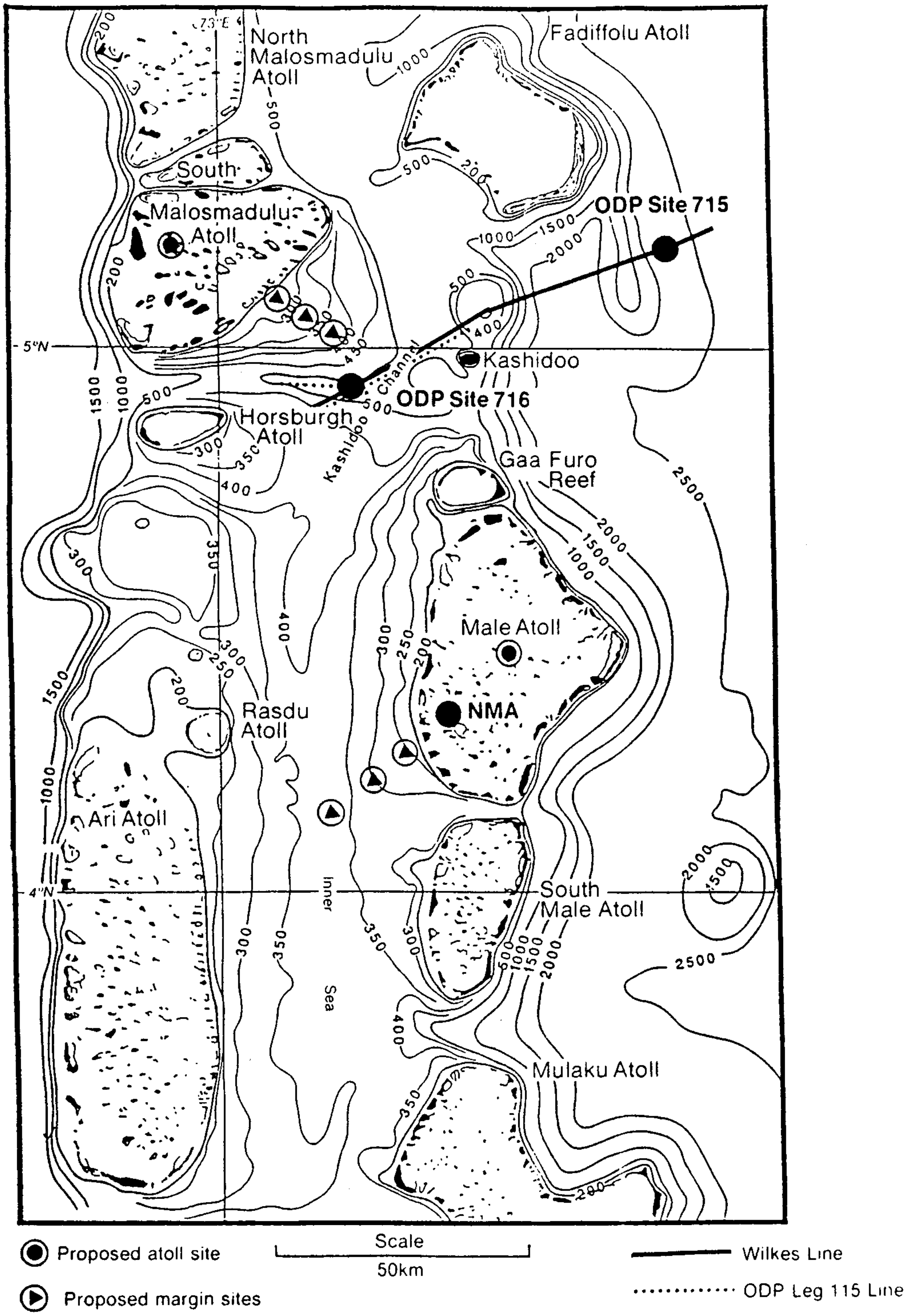

Figure 11. General map of the Maldives showing the double chain of atolls and the internal basin. Elf Aquitaine well NMA, ODP Sites 715 and 716, and the Wilkes and ODP Leg 115 seismic lines are shown in this figure.

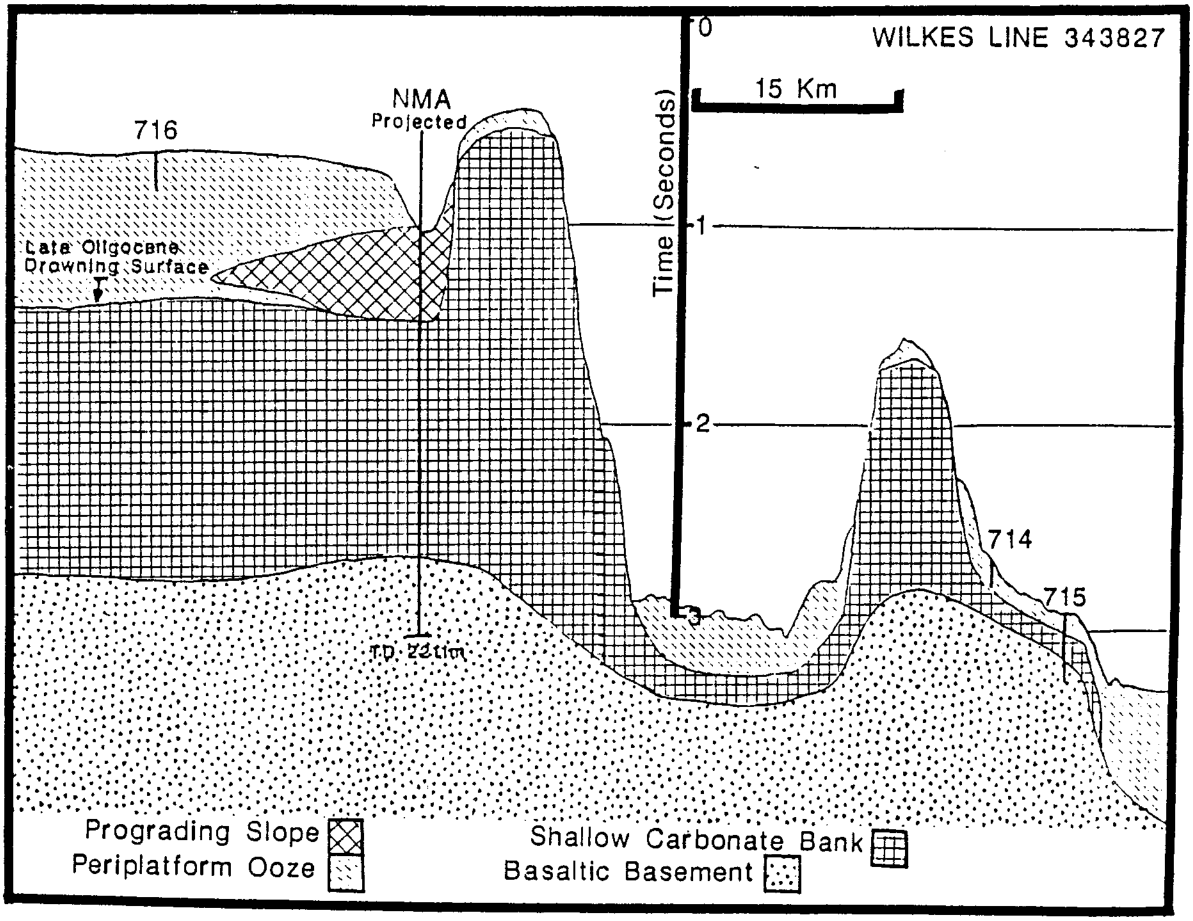

Figure 12. Schematic cross section of part of the Maldives carbonate system, based on the interpretation of one of the Wilkes Lines (see **Fig. 11** for location), showing the establishment of the carbonate edifice on the volcanic basement and its evolution through the Cenozoic. ODP Sites 716, 715, and Elf Aquitaine NMA well are located or projected on the cross section. Note the drowning surface of the shallow carbonate bank in the Oligocene(?) and since then the establishment of the interior basin, partially being filled up by "bidirectional", westward and eastward (shown in **Fig. 14**) progradation of the atolls.

HYPOTHETICAL THERMAL SUBSIDENCE CURVE FOR SITE 715 AND NMA WELL

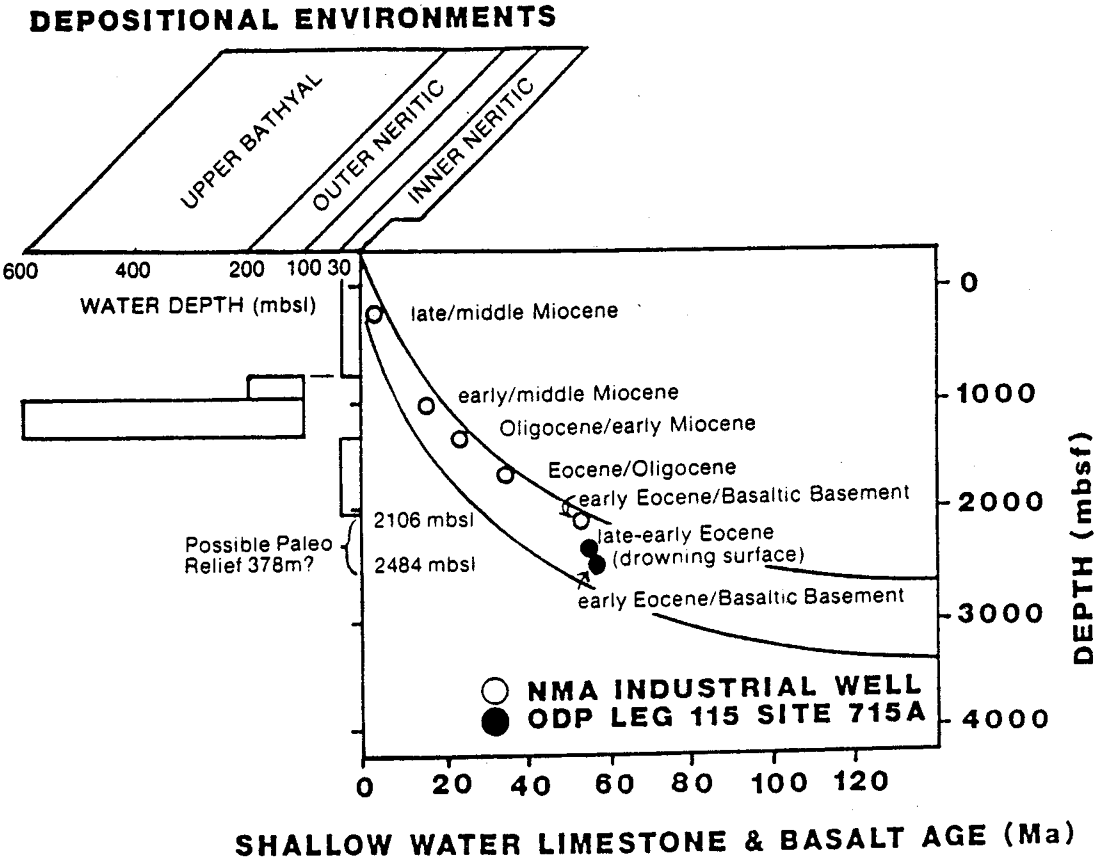

Figure 13. Plots of Elf Aquitaine NMA well (open circles) on a thermal subsidence curve. Note the difference in elevation (378m) between both basaltic/limestone boundaries, although basaltic basement ages are almost the same for NMA (57-58 Ma) and Site 715 (solid circles) (around 55 Ma). The left hand-side of this figure shows schematically the deep (outer neritic/upper bathyal) facies encountered in the NMA well during early and middle Miocene. The NMA well and Site 715 are located in **Figures 11 and 12.**

- <u>Cenozoic Evolution of the Carbonate Edifice</u>: The building of the Maldives carbonate edifice is complex (**Fig. 11, 12, 13** and **14**). The carbonate edifice was a single bank characterized by shallow carbonate reefal environments during the Eocene and the early Oligocene. Sometime during the late Oligocene/early Miocene this large bank was drowned almost completely. During the mid-Miocene the carbonate system started to recover by progradation of the shallow water areas on top of the basin upper bathyal deposits. Progradation is observed on both margins of the atolls, filling in the interior basins from their eastern and western sides (bidirectional progradation; **Fig. 14a** and **14b**). This contrasts with the more common asymmetric carbonate progradation pattern with starved, mainly aggradational windward margins and prograding leeward margins (Eberli and Ginsburg, 1987, 1989; Hine and Neumann, 1977; Hine *et al.*, 1981; Austin, Schlager *et al.*, 1986).

The Maldives Archipelago is unique for studying sea level variations in the Neogene as well as part of the Paleogene (Eocene and Oligocene). Timing and minimum amplitude of the sea-level highstands can be estimated by drilling in atoll highstand deposits (Halley and Ludwig, 1987), whereas timing and amplitude of low- and highstands can be estimated by drilling a transect of sites on highstand and lowstand upper slope deposits.

Atolls

<u>Enewetak</u>

The eustatic record deduced from the stratigraphy of atoll carbonates (the sea-level "dipstick") is an independent check on the eustatic records deduced from seismic stratigraphy and deep-sea foraminiferal oxygen isotopes. A multi-disciplinary approach that integrates seismic, biostratigraphy, petrology and stable isotopes in the analysis of early Miocene to Holocene carbonate sequence on Enewetak provides an excellent example. This approach has already provided a good data base for estimating the history of sea-level fluctuations. Highlights of continued research of this atoll include:

- <u>Seismic reflectors correspond to diagenetic surfaces caused by sea-level fluctuations</u>;

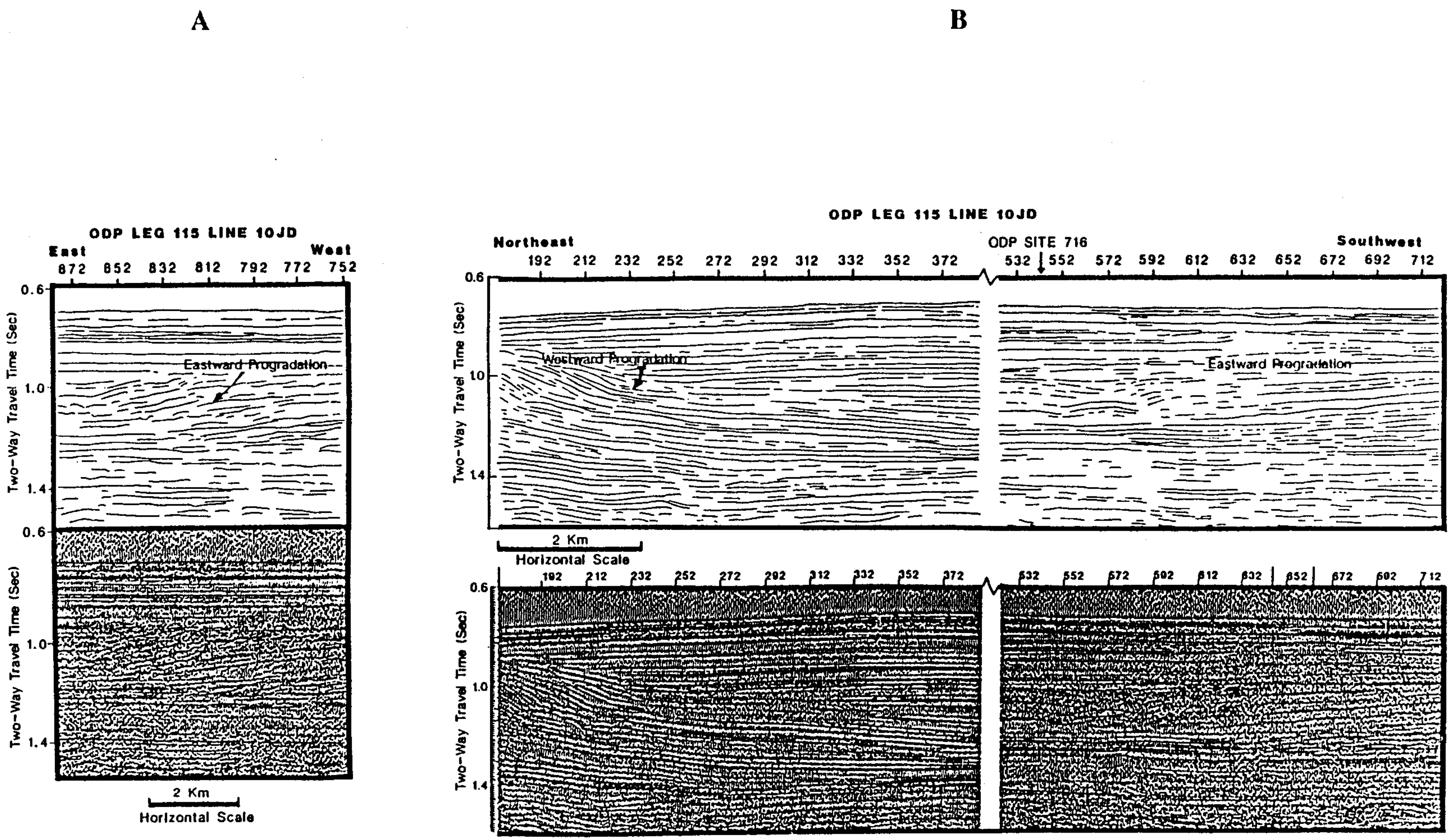

Figure 14a & 14b. Leg 115 **JOIDES Resolution** seismic lines (80 cubic inch SSI water gun; single channel recording) approaching Site 716. Note the bidirectional progradation, with slope progradation toward the east (**Fig. 14a**) and toward the west (southwest?) (**Fig. 14b**). Seismic lines are located on **Fig. 11**.

- A detailed local biostratigraphic zonation based on ostracodes and benthic foraminifers has been developed for shallow-water carbonates on Enewetak that provides excellent correlation not only throughout the atoll, but for a wide area in the Pacific;

- Local biostratigraphic zones correlate with regionally important deep-sea zones using planktic foraminifers and calcareous nannofossils;

- Observed disconformities are products of diagenetic alteration at subaerial exposure surfaces and/or meteoric phreatic lenses according to stable isotope (carbon and oxygen) and petrographic analyses; and

- Constraints on amplitudes of sea-level fluctuations can be obtained from paleotopographic relief estimates developed from seismic profiles tied to boreholes.

Guyots

The flat-topped Cretaceous seamounts or guyots of the Northwestern Pacific (**Fig. 7**) consist of both drowned reefs and reefless volcanoes (Heezen, *et al.*, 1973, Matthews, *et al.*, 1974, Winterer, *et al.*, 1989, Van Wassbergen, *et al.*, 1989, Hamilton, 1956). Many drowned reefs originate as atolls with a perimeter reef enclosing lagoons underlain by as much as 800 m of sediments. Other guyots advanced only to the barrier-reef stage before drowning. Reefal and lagoonal sediments contain a near-continuous succession of reef, backreef and lagoonal environments ranging in age from early to mid-Cretaceous. They lie approximately halfway around the world from the early Cretaceous carbonate platforms of the circum-Atlantic and Tethyan seaways (**Fig. 15**), an important factor in the demonstration of the eustatic nature of sea-level fluctuations.

Ages of lagoonal sequences appear to span 10-25 Ma. A thin cover of later sediments poses no barrier to sampling by **JOIDES Resolution** drilling. Dredge and drilling samples contain datable fossils in both reef and lagoonal facies.

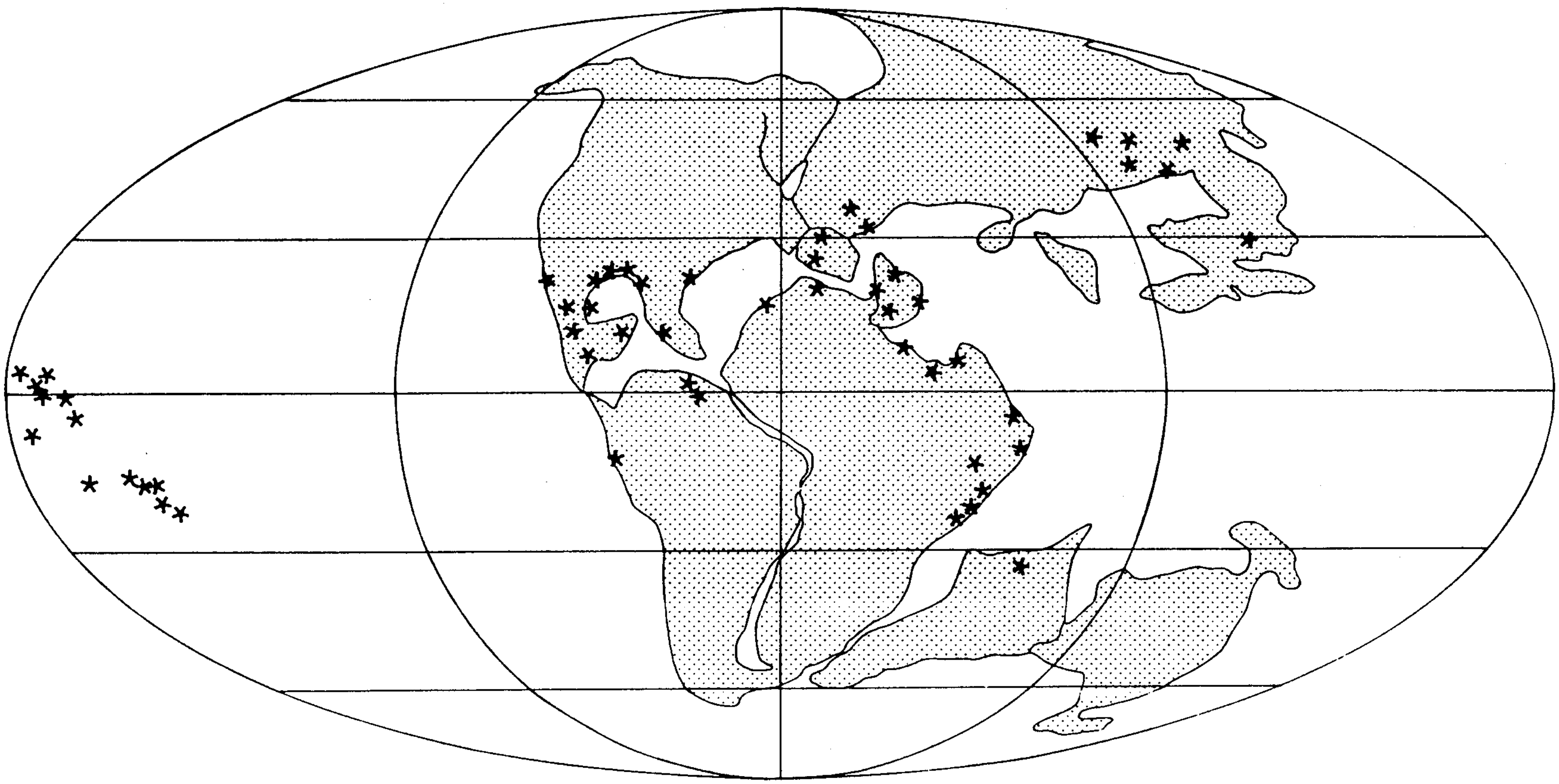

Figure 15. Global paleogeographic reconstruction, Aptian time, showing distribution of rudist reef complexes (modified from C.R. Scotese, pers. comm., 1987).

Cores from the guyots will provide a means of determining timing and amplitudes of sea-level changes during a hothouse interval. Other useful data, including timing and cause of drowning, seamount latitude changes and ages of volcanism will also accrue from such drilling.

The two most attractive areas for drilling are the Japanese seamounts and the Mid-Pacific Mountains. Barrier reefs cap the seamounts of the Japanese Group located between about 30°N and 35°N (**Fig. 7**). Lagoonal sediments are a relatively thin 100 m. Rudists indicate an Aptian-Albian age and dredged basalt gives ages of 102-94 Ma. The Mid-Pacific Mountains located east of the Wake Groups of seamounts at about 20°-25°N appear to consist largely of drowned atolls. Atolls, with diameters ranging up to 40 km, encircle lagoons underlain by 500-800 m of sediments. Reefal ages are Barremian-early Aptian. The drowning unconformity between reefal and overlying pelagic sediments is a karstic erosional surface with a relief of 200 m indicated by the dolines and sink holes.