Science and Technology of Submerged Coral Drilling: A Workshop Report

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International Workshop on Submerged Coral Drilling

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Report from the International Workshop on Submerged Coral Drilling

Preface

This report is a product of an international workshop on submerged coral drilling, which was co-sponsored by the National Science Foundation and JOI/USSAC and held in St. Pete Beach, Florida from September 27-30, 2000. Terry Quinn and Sandy Tudhope organized the workshop, with the assistance of Larry Edwards, Rick Fairbanks, Michael Gagan, and Fred Taylor. The principal objective of the workshop was to have the coral-based-scientific, imaging and geotechnical communities identify how the capabilities of each community could be better integrated to solve the pressing scientific issues that can uniquely be addressed via submerged coral drilling. Thirty-nine scientists and engineers from 8 countries attended the workshop (Appendix I). This report

1. summarizes the state-of-the-science in the coral, imaging and geotechnical communities,
2. demonstrates that the geotechnical and imaging technologies exist TODAY that make the drilling and recovery of coral-reef (and other) deposits from shallow-water depths (0 - 200 m) entirely feasible,
3. documents the compelling scientific issues that can only be addressed by submerged coral drilling, and
4. provides scientists and engineers interested in shallow-water scientific drilling with the requisite background information to communicate with each other across the different disciplines.

Executive Summary

Annually banded massive corals and their associated reefal deposits have some unique attributes that make them exceptional archives of environmental change in the tropics through the Late Quaternary. These include the ability to directly date corals by high-precision, U-series techniques, the proven ability of large corals to yield high-resolution (e.g., ~monthly) multidecadal-to-multicentury long records of past climate variability in the Late Quaternary, and the utility of corals and associated deposits as recorders of past sealevels. Participants in the International Submerged Coral Workshop identified four overarching scientific issues that can be ideally addressed by the drilling of submerged coral reefs:

1. What is the nature and magnitude of tropical climate change on millennial to interglacial timescales? For example, are there major changes in the tropical hydrological cycle from glacial to interglacial conditions; are there changes in the dynamics of the tropical climate system on millennial timescales, and if so what is their relationship to Heinrich events documented in the high and mid-latitudes?
2. How do the dominant modes of tropical climate variability respond to changing climatic boundary conditions? For example, what are the sensitivities of El Niño Southern Oscillation (ENSO), monsoonal, and interdecadal coupled ocean-atmosphere dynamics to changes in orbital forcing, global and regional temperatures, and sealevels over century to glacial-interglacial timescales?
3. What is the timing and magnitude of sealevel variations during the Late Quaternary? To what extent does sealevel respond to millennial-scale climate variability?
4. What is the nature of the radiocarbon timescale between 12 Ka BP to 40 Ka BP, a time when the abundance of fossil trees are insufficient to produce a radiocarbon calibration based on tree rings?

These four scientific questions, along with other compelling questions concerning fluid flow in reefs and reef ecology, require that submerged coral reefs be successfully cored. To achieve the objectives, coring in shallow water depths (0-200 m) is required. The required depth of penetration of the cores would generally be tens of meters, to a few hundred meters maximum. A lively discussion amongst the workshop participants focused on the issue of core recovery in the reefal environment. Complete core recovery is a laudable objective and clearly maximizes the potential scientific return on the drilling. However, it is important to note that a drilling program that focused on recovering only *in situ* coral heads would still permit most scientific objectives related to climate, sealevel and radiocarbon calibration to be met. Clearly, there needs to be a cost/benefit analysis performed for site specific projects relative to the merits of the vastly different approaches to core recovery in the reefal environment.

The first traditional challenge of ocean drilling is the identification of the drilling target, although this challenge may not be as critical in submerged coral drilling as is often assumed. A suite of remote-sensing technologies is available at a reasonable cost to the academic community, ranging from multibeam sonar, side-scan sonar, to very high-resolution (i.e., meter-scale horizontal resolution and sub-meter scale vertical resolution), seismic-reflection profiling. A newer technology called chirp sonar is now being used extensively in siliciclastic environments, where it provides maximum horizontal resolution of 25 cm while providing ~30 m of penetration in unconsolidated shelf siliciclastics. It would be highly desirable to see if the chirp system could be viable tool in submerged coral drilling site surveys.

Submerged coral drilling may involve a completely different approach to pre-drilling target identification and real-time core acquisition compared to the more traditional drilling of ocean sediments and rocks. Land-based drilling on uplifted carbonate islands has unequivocally demonstrated that buried coral heads can be efficiently recovered by using the principles of coral-reef geomorphology even in the absence of geoacoustical surveys. Furthermore, such land-based drilling programs have often used a drilling strategy that emphasized multiple cores, in preference to single (or a few) deeper cores. The scientific rewards for recovering *in situ* coral heads are so large that a few "dry holes" (i.e., those devoid of coral heads) do not necessarily have a significant negative impact on many of the science objectives. Submerged coral drilling will not likely be a process in which a single, deep borehole is made while the ship maintains station for days to weeks at a time. Instead, a much more likely scenario is one in which multiple sites are drilled in close proximity. Any marine-based drilling program for coral reefs must be flexible enough to be able to make numerous station changes as quickly and efficiently as possible. Thus, submerged coral science truly requires a dedicated "fit-to-mission" philosophy to ocean drilling.

The second, and perhaps more daunting, challenge facing a successful coring campaign of submerged coral reefs is the deployment of the "proper tool for the job". Maintaining station, maintaining proper weight on the drill bit, and negating the effects of heave pose significant challenges to drilling in shallow water (< 200 m). Workshop participants identified 17 potential platforms for conducting geotechnical sampling/coring operations ranging from barges, seabed frames, jack-up rigs, vessels and drillships. Barges, vessels and drillships maintain station in shallow-water by 4-point anchoring or by dynamic positioning (DP), although anchoring is more likely in water depths < 75 m. Seabed frames and jack-up platforms minimize problems associated with maintaining station, weight on bit and heave, although there are limitations with some of these platforms in terms of drilling multiple holes in close proximity. A "mining- or mineral-type" drill rig may be best suited for use in a submerged coral drilling program because of the coral-reef lithologies and the science objectives of drilling and recovery of coral heads. This type of drill rig commonly uses a diamond coring system with thin kerf bits, small cores and wireline sampling. For diamond coring with core size HQ (~60 mm) or larger, the diamond core barrel can be interchanged with piston, push, punch or percussion samplers without pulling the drill string. Diamond coring is especially sensitive to any changes in weight on bit, therefore proper heave compensation is critical to successful coring. When drilling is performed from a platform positioned at the sea surface, a riser is likely needed to provide both lateral support to the smaller diameter mining drill rods and to make it possible to re-enter the holes during the drilling operations. Versatility and portability are critical attributes of any drilling platform used for submerged coral drilling.

In summary, DSDP and ODP have been, and IDOP will be, the preeminent program(s) for the drilling and recovery of ocean sediments and rocks. DSDP and ODP have not traditionally been involved in shallow-water science and especially submerged coral reef drilling largely because of technical limitations of a single-ship program, despite the significant scientific returns that such drilling would provide. A new era in ocean drilling is upon us — IODP — and this program needs to embrace a "fit-to-mission" approach so that drilling proposals having high scientific merit will not be denied funding based on perceived technical limitations. Workshop participants endorsed the notion that submerged coral reef drilling could fall under the purview of IODP because decades of previous ocean drilling have resulted in a system that is well equipped to manage science proposals, funding, sample handling and storage, travel and logistics, etc. However, workshop participants also recognized that drilling platforms separate from a "JR-type" drillship are required for a successful submerged coral drilling program. The challenge in front of IODP is to be flexible enough to drill the scientific proposals that are highest ranked, regardless of the platform that is required to accomplish the highest priority scientific objectives, as long as they are reasonable from an economic perspective. Workshop participants strongly endorsed the concept of a tripartite drilling approach for the IODP consisting of a non-riser drillship, riser drillship and a suite of alternative platforms.

Recommendations

1. Strongest possible support for Europe's contribution of alternative platforms to IODP to compliment the contributions of the US (new non-riser drillship) and Japan (new riser drillship).
2. The compelling scientific rewards behind shallow-water drilling and especially submerged coral drilling justifies the inclusion of such alternate platform drilling as an integral part of IODP. The vast experience in proposal and project management, core handling and core repositories, technical support, publication protocols, etc. provided by ODP/IODP provide a powerful incentive for the submerged coral drilling community to want to be part of this global drilling program.
3. The determination of the most appropriate platform to drill highly ranked scientific proposals should be made by a "geotechnical" committee consisting of scientists and engineers. In such a system, PIs whose drilling objectives require alternate platforms would concentrate their efforts on the science in the proposal. The "geotechnical" committee would work with the PIs of the highly ranked scientific proposal to determine all the drilling parameters and variables needed to form a "request for drilling bids". The global geotechnical drilling community could then provide a series of bids for the successful completion of the scientific objectives. The "geotechnical committee" would evaluate all of the bids and recommend the best drilling solution — riser, non-riser or alternate platform. Such a system would provide immediate benefit to siliciclastic and carbonate margin communities, as well as to the submerged coral drilling community. Perhaps just as important, such a system would permit the two drillships of IODP to concentrate their efforts where they are best suited (e.g., deep water/deep penetration/piston coring), while leaving shallow-water drilling to platforms specifically designed for drilling in these waters.
4. Release time for an ODP engineer for consulting on drilling proposals involving alternate platforms.
5. Promote/facilitate an integrated approach to site-survey work in remote areas of the tropics to get the benefit of the economies of scale.
6. Development of an international tropical science initiative. The IODP should play the leading role in the ocean portion of this initiative.
7. Establish official liaison relations with other working groups that require alternative platforms (e.g., SHALDRILL, MARGINS, ARTS, PAGES-CLIVAR, etc....)
8. Establish a web page to facilitate proposal generation by providing a one-stop location for information required for proposals involving submerged coral drilling

Workshop Report

Many of the scientific objectives of submerged coral drilling are directly related to investigating the nature and causes of tropical climate variability, and their global repercussions, on interannual through to glacial-interglacial (10^5 year) timescales. Therefore, before detailing the ways in which submerged coral drilling will yield answers to some crucial climatological questions, here we summarize the state of knowledge on several key modes of variability in the tropical climate system.

1. Tropical Climate Variability

The tropical ocean is the primary source of energy and water vapor to the atmosphere and interactions between the tropical ocean and atmosphere have global climate ramifications on interannual, decadal and, arguably, glacial-interglacial timescales. The recent suite of intensive observational programs (e.g., TOGA/GOALS-related programs) has led to a dramatic increase in our understanding of tropical ocean-atmosphere interactions. However, instrumental climate records from the tropics, especially continuously recorded time series, are scarce and short. Salinity time series are limited. The limited number of realizations available in the instrumental record to study interannual climate phenomena like the El Niño Southern Oscillation (ENSO), much less decadal-to-centennial climate phenomena, means that proxy records must be used to characterize the nature of tropical climate variability in the pre-instrumental period. Modern and fossil corals are a most promising proxy to study the tropical ocean-atmosphere component of the climate system.

The subsequent sections on aspects of tropical climate variability (1.1, 1.2 and 1.3) are based on the ARTS (Annual Record of Tropical Systems) Report (Dunbar and Cole, 1999).

1.1 ENSO and Decadal ENSO-like Variability

The ENSO system dominates interannual variability of the ocean and atmosphere in the tropical and subtropical Pacific (Figure 1, upper series, and Figure 2, upper panel). This signal propagates through the global atmosphere to leave its imprint on planetary systems as diverse as polar sea ice, maize growth in Africa, and rainfall in Florida. ENSO results from instabilities in the coupled ocean-atmosphere system that drive interannual shifts in oceanographic and atmospheric variables throughout the Pacific. Features that are dramatically influenced by ENSO (and participate actively in the evolution of ENSO anomalies) include the intensity and location of atmospheric convection over the western Pacific, the east-west equatorial Pacific sea-surface temperature (SST) gradient, the strength of the zonal atmospheric Walker circulation, and the three-dimensional distribution of ocean currents. Although ENSO variability is defined on an interannual scale, decadal variations in ENSO-related parameters are clear in paleoclimatic records and have recently emerged from the lengthening instrumental record. Seasonal, interannual, and decadal modes of variability appear to change in concert through time in the tropical Pacific. How these changes modulate ENSO's extratropical influences remains unknown. The sensitivity of ENSO and its teleconnections to rising greenhouse gas concentrations also requires further investigation.

A detailed analysis of the historical record spanning the past century has produced a new view of the spatial patterns of ENSO variability through time (Allan et al., 1997). This compilation suggests that rainfall, SST, and wind field anomalies associated with ENSO events (both "warm" and "cool") differ strongly from event to event, and that the centers of action also shift. For example the eastern pole of the Southern Oscillation of sealevel pressure, conventionally defined as Tahiti for the construction of a standard Southern Oscillation Index (SOI), appears to have wandered during the present century. In addition, comparison of both instrumental and paleoclimatic records of US drought with ENSO records shows that patterns of ENSO-related drought in the US have not remained stable over this interval (Cole and Cook, 1998). Clearly, the interannual ENSO phenomenon experiences significant variations from its canonical state, and the predictability of this system and its impacts depends on understanding these variations.

Instrumental and paleoclimatic data indicate significant decadal variability in the tropical Pacific climate system (Figure 1, lower series). This variability is similar in spatial structure to ENSO, although more proniunced in the subtropics (Zhang et al., 1997; Figure 2). Although primarily a low frequency climate anomaly, the changes in amplitude can be rapid and include the well documented Pacific basin "regime shift" of 1976 (Trenberth and Hurrell, 1994; Graham, 1994). The physical mechanisms responsible for decadal ENSO-like variability are not known, but the resulting climate anomalies are significant. Furthermore, the interannual ENSO and decadal ENSO-like phenomena are associated with qualitatively different climate anomalies at mid- and high latitudes (Ebbesmeyer et al., 1991; Zhang et al., 1997; Mantua et al., 1997; Figure 3). Climate anomalies associated with interannual ENSO variability feature a more zonal perturbation in the western-hemisphere circulation at mid-latitudes and explain a lower fraction of the variance in the mid-latitude climate anomalies. The ENSO-like decadal variability features a classic Pacific North America (PNA) pattern (Kawamura, 1994) and explains a significant portion of winter climate anomalies in the mid-latitude northern hemisphere (Graham, 1994; Zhang et al., 1997; Bitz and Battisti, 1999).

Numerical and statistical models indicate skill in predicting the state of ENSO about a year in advance (Zebiak and Cane, 1987; Barnett et al., 1988; Latif et al., 1998). However, there are substantial differences in forecast skill from decade to decade (Chen et al. 1995, Balmaseda et al., 1995). The cause of these changes is not clear; leading candidates include a change in the basic state of the tropical climate system and a change in the phase of the decadal ENSO-like climate anomaly (i.e., the 1976 regime shift). Both of these possibilities suggest a need for improved understanding of the decadal to centennial variations in the tropical Pacific.

The relationship of ENSO to anthropogenic warming remains an important and controversial topic. Several studies support potential links between ENSO and increasing greenhouse gas concentrations. The shift towards generally more ENSO-like conditions in 1976 is consistent with atmospheric GCM predictions of an intensified hydrologic cycle under doubled CO_2 scenarios (Graham, 1995). Both the recent tendency for more ENSO warm anomalies and the prolonged warm anomaly that persisted through the early 1990's are unprecedented in the instrumental climate record. This result raises the question of whether recent ENSO anomalies occurred as a result of increasing greenhouse gases (Trenberth and Hoar, 1996; Rajagopalan et al., 1997). Yet studies utilizing paleoclimatic records suggest that similar anomalies of the duration of the 1991-4 event have occurred over the past three centuries, implying no relation to recent greenhouse gas increases (Allan and D'Arrigo, 1999). Greenhouse gas increases may ultimately result in cooler SST in the easternmost tropical Pacific via a process involving warming of the western Pacific, a stronger east-west equatorial SST gradient, and resulting stronger trade winds that enhance upwelling of cool water in the east (Cane et al., 1997). Attributing any observed recent changes to greenhouse gas forcing ultimately requires a more extensive baseline of ENSO observation than currently exists – temporally, spatially, and with respect to multiple processes.

ENSO sensitivity and predictability would be of less interest if ENSO affected only the tropical Pacific, but this system produces a far-reaching set of global climate teleconnections that allows the predictability of ENSO to be translated to predictability of anomalies in many other regions, tropical and extratropical (Figure 3). A GCM-based study indicates that ENSO teleconnections may vary as background climate changes (Meehl and Branstator, 1992). A recent characterization of the Pacific decadal pattern (Zhang et al., 1997) indicates that the mid-latitude anomalies associated with decadal variations in the Pacific differ from those associated with interannual ENSO variations (Figure 4). Variations in ENSO teleconnections may result from changes in the locations of centers of action, seasonal timing, intensity of anomalies or from the interaction of ENSO with mid-latitude anomalies or other decadally varying aspects of climate (Simmons et al., 1983, Barsugli et al., 1996; Kumar and Hoerling, 1997). Understanding the nature and causes of teleconnection instability is crucial for ongoing climate prediction efforts related to ENSO.

1.2 The Monsoon System

The irregularities of the monsoon govern food production for billions of people, often in countries where poorly developed infrastructure and lack of financial and agricultural reserves exacerbate vulnerability to climate variability. A weak monsoon can bring drought, an abundant one can result in flooding and infrastructure damage. Early attempts at monsoon prediction led to the discovery of the Southern Oscillation (Walker, 1923, 1924) but monsoon predictability remains an elusive goal (Webster et al., 1998). Knowledge of the fundamental cause of monsoon circulation, the imbalance in the rate and magnitude of seasonal heating and cooling over the land and ocean, has not yet led to a thorough understanding of the factors that govern interannual and decadal variations in this system.

ENSO variations are linked to monsoon strength in many regions. In Australia the monsoon is weakened during ENSO warm phases as the convective system that usually resides over the maritime continent migrates northeastward. In Asia, although the monsoon and ENSO are linked, a weak monsoon tends to precede the season of strong ENSO warm conditions, reducing the utility of ENSO as a predictor (Webster and Yang, 1992). In East Africa, rainfall during the lesser of the two annual rainy seasons (October-November) is strongly correlated with ENSO but the strength of the more substantial rainy period (March-May) is unrelated (Hastenrath et al., 1993). These linkages need to be defined through time and characterized with other influences on monsoon rainfall when ENSO is weak (e.g. 1920-1950) or, for whatever reason, does not correlate well with monsoon rainfall.

The cause of interannual to centennial variability in the Asian monsoon remains a subject of debate; better observations of this long-term variation will help to distinguish among candidate hypotheses. In general, two classes of explanations have been put forth: those attributing monsoon variations to oceanic conditions and those invoking land-surface processes. For example, studies exploring the impact of Indian Ocean SST on Asian monsoon strength have reached disparate conclusions, perhaps as a consequence of limited SST data (Terray, 1995). South of the equator, warm SST's in the boreal summer can induce rising air that acts as an alternative site for moisture convergence in the region, reducing available moisture for convergence over land and leading to a weak monsoon (Cadet, 1979; Cadet and Reverdin, 1981; Shukla, 1987). Alternatively, land-surface feedbacks related to Eurasian snow cover, vegetation, and soil conditions may impart interannual and longer variability to the monsoon due to changes in the radiation balance over land (Vernekar et al., 1995).

With respect to the East African monsoon, large-scale SST fields likely play a role in the seasonal transit of the Inter-Tropical Convergence Zone (ITCZ) southwards from the Asian continent (following boreal summer), as it crosses the East African coast in the boreal fall and spring, and moves back towards Asia the following summer. However, this relationship has not been well defined. East African coastal rainfall responds positively to warm SST anomalies in the western Indian Ocean and cool SST anomalies in the eastern portion of the basin are also involved, likely as a component of a zonal ocean-atmosphere circulation system (Webster et al., 1999; Clark et al., 2000; Figure 5).

The potential exists to test proposed forcings and mechanisms of monsoon variability with concurrent records of both surface ocean and land conditions from annually resolved paleoclimate archives. For example, SST reconstructions from Indian Ocean corals reveal substantial variability on decadal time scales, which is poorly documented by the very limited instrumental SST record. In a Seychelles coral, the decadal patterns of variation correspond with Indian monsoon rainfall indices, suggesting that long-term regional rainfall variability may originate at least in part from the ocean (Charles et al., 1997). This and other coral records spanning 1800-1995 A.D. (Cole et al., 2000) also indicate a long-term warming trend leading up to 1986-1995 as the decade with the warmest SSTs in the past two centuries. This trend was identified from the much shorter instrumental record but dismissed due to possible biases in the data (Terray, 1995).

1.3 The Atlantic Dipole

Regionally coherent SST anomalies north and south of the equator in the Atlantic govern the strength and position of the ITCZ and influence the variability of rainfall on adjacent continents, particularly in the Nordeste region of Brazil (Figure 6) and to a lesser extent, the African Sahel (Hastenrath and Heller, 1977; Hastenrath and Lamb, 1983; Moura and Shukla, 1981; Folland et al., 1986; Hastenrath, 1990; Servain, 1991; Hastenrath and Greischar, 1993; Enfield and Mayer, 1997). Hastenrath has identified the interhemispheric tropical SST gradient as especially important in this regard: when the northern tropical Atlantic is anomalously warm and the south anomalously cool, the ITCZ is displaced northwards and rainfall is increased in the Sahel and decreased in the Nordeste. When the opposite SST configuration prevails, the Sahel suffers from lack of rain and the Nordeste is unusually wet. Although on interannual time scales, the variability in northern and southern tropical Atlantic SST appears uncoupled (Houghton and Tourre, 1992), on decadal scales the interhemispheric SST gradient appears to reflect a dipole, with inversely correlated anomalies on either side of the equator.

Chang et al. (1997, 1998) used singular value decomposition of SST and wind data to describe this decadal SST dipole (Figure 7). Based on a series of model experiments, they propose a mechanism by which ocean-atmosphere interaction maintains this oscillation on a decadal time scale. The proposed mechanism involves a balance between SST anomalies reinforced by anomalous winds and negative feedback associated with the cross-equatorial transport of heat by ocean currents. One explicit conclusion of this study is that the Atlantic dipole is not strongly influenced by remote or global patterns but depends on local mechanisms. However, other studies have indicated that at least in the southern tropical Atlantic, SST anomalies are correlated with ENSO interannually (Enfield and Mayer, 1997; Hastenrath et al., 1987; Curtis and Hastenrath, 1995), and in the northern tropics, links to the North Atlantic Oscillation are possible (Lamb and Peppler, 1992; Kawamura, 1994; Hoerling et al., 2001). The mechanism proposed by Chang et al. (1997, 1998) also requires that shifts between phases of the dipole are triggered by circulation changes that alter cross-equatorial heat transport.

2. Coral-based Science

2.1 Corals as Chronometers

Most massive reef corals live at depths of < 20 m and grow continuously at rates of 6-25 mm yr^{-1}, producing annual density bands that provide time markers for the development of long chronologies (Knutson et al., 1972; Figure 8). Density bands provide an inexpensive, fast, and precise chronology of skeletal growth with many coral records having absolute annual chronologies. Where banding is absent or poorly defined, the seasonal cycling of detailed oxygen or carbon isotope records (Fairbanks and Dodge, 1979; Cole et al., 1993; Gagan et al., 1996; Evans et al., 1998; among others) can be used to either fill gaps or even to establish relatively long chronologies. Application of cross dating and multiple age-specific tracers should allow most coral records to achieve true annual chronologic precision.

2.1.1 Uranium Series Methods

Dating of modern and fossil corals by uranium-series methods provides excellent chronologic control for late Quaternary and Holocene geology. Uranium-series dating methods originate from two separate decay chains parented by ^{238}U and ^{235}U. These parents become fractionated from certain daughter products, including ^{230}Th and ^{231}Pa respectively, during the weathering process because uranium is soluble in most natural waters, while Th and Pa are essentially insoluble. Thus, carbonates precipitated out of natural waters will contain some uranium, but essentially no thorium or protactinium. The in-growth of ^{230}Th from the decay of ^{238}U is the backbone of the main chronometer, which finds one of its optimal applications in fossil corals due to the high concentration of uranium (~3 ppm) in coralline skeletal aragonite. The half-life of ^{230}Th is ~75,000 years, extending its range to ~450,000 years for coral that has been perfectly preserved. ^{231}Pa has a half-life of ~33,000 years, and an applicable range of ~200,000 years. High-precision techniques utilizing thermal ionization mass spectrometry (TIMS) yield typical precision values that range from 2 years in a 100-year old sample to 10,000 years in a 350,000-year old sample.

Many studies have employed ^{230}Th dating of fossil corals to study a wide range of problems, from neotectonics to sealevel history to ^{14}C-calibration. For older corals especially, the limitation is not usually the precision in the determined age, but in the preservation of the sample, as most-older corals have come from uplifted regions. With exposure to meteoric waters, coralline aragonite can be altered to calcite, potentially changing the uranium-series isotopic composition and thus shifting the ^{230}Th age from its true value. Screening for calcite is a first-order check for alteration, however, measuring the uranium-isotopic composition provides a means of testing for subtle amounts of diagenesis. ^{234}U, another daughter of ^{238}U, is also fractionated from its parent and is present in excess in ocean water. The modern marine $^{234}U/^{238}U$ ratio is 1.144 (Chen et al., 1986) (if there was no fractionation, the ratio would be 1), whereas some uplifted fossil corals older than 100,000 years have ratios that imply an initial marine value of > 1.2. $^{234}U/^{238}U$ values >~1.17 are extremely unlikely to have occurred in the last 200,000 years (Edwards, 1988; Hamelin et al., 1991; Richter and Turekian, 1993), given the residence time of U in the ocean (~400,000 years; Ku et al., 1977), implying that corals with elevated $^{234}U/^{238}U$ ratios have been altered by diagenesis. Further, several studies have suggested that the marine $^{234}U/^{238}U$ ratio has not changed significantly in 200,000 to as long as 400,000 years (Gallup et al., 1994; Henderson et al., 1993; Henderson, 2000). Thus, checking the $^{234}U/^{238}U$ ratio has become a standard means of testing for the quality of the coral sample, and thus the reliability of the ^{230}Th age (e.g., Stirling et al., 1995). Recently, ^{231}Pa dating has become important as an independent chronometer, providing a test of concordance between ^{230}Th and ^{231}Pa ages (Edwards et al., 1997).

Submerged corals that have remained bathed in seawater, in contrast to emergent corals, are much more likely to give an initial $^{234}U/^{238}U$ ratio matching modern marine values. For instance, the Barbados drillcore that succeeded in recording the sealevel rise since the last glacial maximum (Fairbanks, 1989), includes 24 ^{230}Th dates from corals that grew between 7,000 and 22,000 years ago (Bard et al., 1990). Twenty of these samples have initial marine $^{234}U/^{238}U$ ratios that are within error of the modern value. Contrast this with samples collected from an extremely well preserved outcrop in an uplifted coral terrace on Barbados that was formed ~200,000 years ago (Gallup et al., 1994), where only 2 of 9 samples meet the initial $^{234}U/^{238}U$ ratio criteria. The improved preservation in submerged samples seems to hold for older specimens as well, from the small amount of data available. For example, in two separate studies where limited coral material >300,000 years old was recovered, one out of three samples (ODP drilling of the Bougainville Guyot (Taylor et al., 1994)) and one out of four samples (dredged from 2 km depth in the Huon Gulf, New Guinea (Galewsky et al., 1996)) had initial $^{234}U/^{238}U$ ratios matching the modern value. Well-preserved fossil corals of equivalent age on uplifted terraces do not appear to exist.

Thus, experience dictates that uranium-series dating methods provide precise, accurate chronology for coral material younger than 20,000 years and that, for older corals, extensive submerged coral drilling is likely to recover information, paleoclimatic, tectonic, and otherwise, that cannot be obtained through land-based coral studies.

2.1.2 Radiocarbon Methods

The large amount of material available from cores of fossil coral make them ideal candidates for radiocarbon dating. With the advent of AMS-technology sample size requirements have dropped by several orders of magnitude compared to traditional beta counting techniques. The majority of AMS laboratories make "standard" analyses on 1 mg carbon targets (nominally 10 mg of aragonite) with routine analyses on samples approaching 50 micrograms of carbon.

There are two sources of error in reaching a radiocarbon date: the errors associated with acquiring the 14/12C (or 14/13C) ratio to a prescribed precision (vis a vis, counting statistics) and the value and error or reproducibility of the background subtraction used in determining the sample's age. Additionally, there are questions related to sample pretreatment protocol and the appropriateness of a given background material. Both of these (latter) questions are directly related to the geologic history of the sample suite in question. For example, has the sample interacted with groundwater? Or has the sample been subjected t subaerial diagenesis?

In general, carbonate samples that have been subaerially exposed, either in an arid or humid environment, have the opportunity to provide inaccurate and young ages if they are not adequately pretreated. The impact of the young or modern carbon contribution is larger with the true age of the sample. As a case in point a 1% modern carbon contribution to a sample that in truth should be 14C-free will give an apparent age on the order of 37,000 years. If the true-age of the sample were 12,000 years, then this contaminant would yield an age ~350 years too young. Pre-treatment of carbonate material for 14C dating includes physical cleaning and chemical leaching (usually with dilute HCl) and less frequently, an oxidative step utilizing hydrogen peroxide.

The results of leaching experiments is inconclusive if the desired result is determining a pre-defined and standardized protocol: in some instances there is no difference between samples weakly leached (4-7% mass loss) or harshly leached (>25% mass loss). In other experiments, significant differences exist regardless of the true age of the sample. In general, samples that have been continuously submerged (up until the time of drilling) tend to give consistent results regardless of protocol, whereas those samples that have been subaerially exposed for a significant portion of their life show an "aging" of the results when subjected to chemical leaching. In order to avoid and minimize inappropriate interpretations we suggest a working protocol for coral samples whereby samples should be physically cleaned (vis a vis, an interior sample), coarsely crushed, and subjected to a 30% (mass loss) leach using dilute HCl. Additional thought should be given to samples that give results greater than 30,000 years (Fraction of modern carbon [Fm] 0.02) depending on availability of sample material and the geologic and climatic history that the sample has been exposed to.

With regards to analytical precision on samples that span the last glaciation, many AMS laboratories are count limited and may lack an appropriate 14C-free background material. Clearly, a hand sample from the subaerially exposed Huon VII reef complex at New Guinea would not be an appropriate background material for a sample recovered off Barbados that has never been subaerially exposed. For those laboratories that are not count limited (i.e., the ion source and AMS beamline architecture (acceptance) are such that high count rates are possible within a reasonable amount of time) a majority of the error comes from the value and reproducibility of the background material. At the Center for Accelerator Mass Spectrometry at Lawrence Livermore National Laboratory, the source output is consistently around 250µA of C^- so that one can count an older (Marine Isotope Stage 2 and 3) sample to a precision better than 1% over a twenty or twenty-five minute span, accumulated in several shorter runs for internal consistency. Accelerators with source output (and small acceptance) on the order of 35-50µA of C^- will take a proportionally longer time to acquire similar precision results.

2.2 Corals as Climate Proxies

2.2.1 Modern Corals and Climate

Massive corals growing in the reef ecosystems of the tropics provide some of the richest paleoclimate archives in the world. Corals are particularly useful paleoclimate recorders because they are widely distributed, can be accurately dated, and contain a remarkable array of geochemical tracers within their skeletons. During the last decade, there has been a concerted effort to identify new climatic tracers in corals and develop more sophisticated techniques for data extraction and measurement. As a result, a multi-proxy approach to coral-based paleoclimatology is emerging that is yielding new insights into tropical paleoclimates. Geochemical tracers commonly used in coral paleoclimatology studies include oxygen isotopes and element/Ca ratios (e.g., Sr/Ca, Mg/Ca, U/Ca and Ba/Ca), which are briefly summarized in subsequent paragraphs. Variations in coral growth rate (e.g., Lough and Barnes, 1997) and in annual luminescent banding (e.g., Isdale et al., 1998) also record climatic variations. Readers are encouraged to read the recent summaries by Dunbar and Cole (1999) and Gagan et al. (2000) for a more detailed discussion of the use of corals as climate proxies.

Many coral studies have used oxygen isotopic measurements because they are readily available and relatively straightforward to interpret. Oxygen isotope ratios ($\delta^{18}O$) of coral aragonite provide a useful history of environmental variability. In oceanic settings where the oxygen isotopic composition of seawater is thought to be constant, coral skeletal $\delta^{18}O$ records SST variability, usually following the standard temperature dependence for carbonates (Epstein et al., 1953). The oxygen isotopic composition of coral aragonite is offset by a biological non-equilibrium component that appears to be stable through time, as long as a consistent, maximum growth axis is sampled within a coral colony (Weber and

Woodhead, 1972; Dunbar and Wellington, 1981; Patzold, 1984; McConnaughey, 1989; Winter et al., 1991; Shen et al., 1992; Gagan et al., 1994; Leder et al., 1996; Swart et al., 1996; Wellington et al., 1996; Linsley et al., 2000a). When seawater $\delta^{18}O$ varies in response to changes in the balance between precipitation, evaporation, and water advection, the coral $\delta^{18}O$ changes accordingly (Swart and Coleman, 1980; Dunbar and Wellington, 1981; Cole et al., 1993; Gagan et al., 1994; Linsley et al., 1994; Fairbanks et al., 1997). Long records of coral $\delta^{18}O$ have been used to develop precipitation reconstructions from sites where seawater $\delta^{18}O$ correlates with rainfall (Cole et al., 1993; Linsley et al., 1994; Tudhope et al., 1994). Published coral time series (Figure 9) from modern corals have provided new information on environmental changes in surface ocean conditions over the past several centuries in many regions of the tropics including changes in the state of ENSO, interdecadal linkages between Indian and Pacific Ocean, changes in salinity related to movement of the ITCZ, possible changes in fresh water storage in the Western Pacific Warm Pool, and the climatic effects of volcanic eruptions (Patzold, 1984; Druffel and Griffin, 1993; Dunbar et al., 1994, 1996; Heiss, 1994; Linsley et al., 1994, 2000a; Charles et al., 1997; Crowley et al., 1997; Quinn et al., 1998; Urban et al., 2000). Similar information can be gleaned from the study of fossil corals that can only be recovered through a submerged coral-drilling program.

Element/Ca ratio analysis of coral skeletal material has also been used to calculate sea-surface temperatures of the tropical oceans. A well-established relation exists between SST and Sr/Ca (e.g., Weber, 1973; Smith et al., 1979; Beck et al., 1992; Shen et al., 1996; Alibert and McCulloch, 1997; Schrag, 1999; Linsley et al., 2000b), SST and Mg/Ca (e.g., Mitsuguchi et al., 1996), and SST and U/Ca (Min et al., 1995; Shen and Dunbar, 1995). The sensitivity of Sr/Ca is ~0.7% per 1 C change in SST (Beck et al., 1992), whereas the sensitivity for Mg/Ca is ~3.5% per 1 C change in SST (Mitsuguchi et al., 1996), and for U/Ca the sensitivity is ~4.0% per 1 C change in SST (Shen and Dunbar, 1995; Min et al., 1995). In theory, a multi-proxy approach that combines elemental ratios and oxygen isotope data should permit the isolation and identification of the specific thermal and hydrologic variations at a coral site (McCulloch et al., 1994; Gagan et al., 1998). Skeletal Ba/Ca and Cd/Ca ratios have been proposed as proxies for upwelling intensity due to the nutrient-like distribution of Ba and Cd within the ocean (Lea et al., 1989; Shen et al., 1987). In coastal setting, Ba/Ca may also be a proxy for riverine run-off (e.g.,

In summary, records of geochemical and growth variations within a coral skeleton that have seasonal to annual resolution can contribute to resolving key uncertainties in our knowledge of tropical climate. For example, published time series (e.g., Figure 9) from modern corals have provided new information on environmental changes in surface ocean conditions over the past several centuries in many regions of the tropics including changes in the state of ENSO, interdecadal linkages between Indian and Pacific Ocean, changes in salinity related to movement of the ITCZ, possible changes in fresh water storage in the Western Pacific Warm Pool, and the climatic effects of volcanic eruptions (Patzold, 1984; Druffel and Griffin, 1993; Dunbar et al., 1994, 1996; Heiss, 1994; Linsley et al., 1994; Charles et al. 1997; Crowley et al., 1997; Lough and Barnes, 1997; Isdale et al., 1998; Quinn et al., 1996, 1998; Klein et al, 1997; Urban et al., 2000; Linsley et al., 2000; Evans et al., 1998, 2000; Cole et al, 2000). Similar information can be gleaned from the study of fossil corals that can only be recovered through a submerged coral-drilling program. The aragonite skeletons of reef-building corals carry a diverse suite of isotopic and chemical indicators that track water temperature, salinity, and isotopic composition as well as site-specific features including turbidity, runoff, and upwelling intensity. By documenting the natural behavior of these systems, we can assess the nature and extent of natural variability due to stochastic processes and internal oscillations in the coupled climate system, as well as assessing their sensitivity to various forcing factors including natural phenomena, such as solar and volcanic changes, and anthropogenic inputs such as increasing greenhouse gas concentrations and land-use changes. A high priority in coral research is to produce quantitative indicators of specific aspects of climate that can be integrated with other high-resolution paleoclimate data, including tree rings, ice cores, and varved sediments, and compared with climate model output to help assess and improve model performance. The ultimate goal of these studies is to contribute to the development of an enhanced predictive capability for future climate on timescales of relevance to society.

2.2.2 Fossil Corals and Past Climates

Fossil corals offer a unique archive of tropical climate variability throughout the late Quaternary (Figures 10-12). Key attributes of the corals include their widespread distribution in the tropical oceans, the exceptional temporal resolution (sub-annual within individual coral records), the suitability of coral skeletons for precise high-precision U-series dating, and the suite of climate proxies available in the skeletal geochemistry. Fossil corals may be used to quantify the range of natural variability within the tropical climate system under conditions of relatively uniform climate forcing (e.g., the late Holocene), as well as investigating the influence of changing climatic boundary conditions (e.g., changed orbital forcing and 'glacial-interglacial' changes in sea-level and global climate) on tropical climate. Furthermore, they may be used to identify leads and lags in the climate system, thereby helping elucidate the mechanisms of climate change, and the role of the tropics in mediating global change, on interannual through to glacial-interglacial timescales. Some of this potential is illustrated by a number of published studies on fossil corals which have yielded information about past changes in tropical SST (e.g., Beck et al., 1992, 1997; Guilderson et al., 1994; McCulloch et al., 1996; 1999), hydrologic balance (e.g., Klein et al., 1990; Gagan et al, 1998), ocean mixing (e.g., Edwards et al., 1993), and ENSO variability (e.g., Tudhope et al., 2001).

The nature of tropical involvement in past global climate change remains poorly understood. However, changes in tropical SSTs appear to have lead changes in global ice-volume over the past few glacial-interglacial cycles (e.g., Lea et al., 2000), suggesting the possibility that the tropics are directly involved in translating the relatively weak orbital forcing to the observed glacial-interglacial climate response of the global system (e.g., Cane, 1998; Clement et al., 1999). The tropics may also be directly implicated in mediating global climate variability on orbital precession timescales (e.g., Clement et al., 2000). The global climate change debate has led to renewed interest in analyzing corals that grew during times when the earth was warmer than today, or was warming rapidly. Although these climates of the past are not analogues for a CO_2-warmed Earth (Crowley, 1990), such records will certainly yield perspectives on processes driving the climate system (Rind, 1993). Addressing this issue requires robust estimates of past mean climate conditions and past climate variability, and precise dating to identify leads and lags. These data sets will be particularly useful for understanding the sensitivity of climatic processes to global climate change, at time-scales that are relevant to society.

The precise measurement of the Sr/Ca ratio in coral aragonite offers a promising thermometer for reconstructing SSTs of the distant past (see section 2.2.1). The applicability of this technique to fossil corals depends on the stability of the Sr/Ca ratio of seawater through time. This condition holds today because high-precision measurements of Sr/Ca in modern reef waters show relatively little variability, equivalent to offsets of only 0.2°C in reconstructed SSTs (de Villiers et al. 1994; Shen et al. 1996). However, recent models by Stoll and Schrag (1998) suggest that dissolution of Sr-enriched aragonite exposed on continental shelves during sealevel low stands (i.e., the LGM) will increase the Sr/Ca ratio of glacial seawater, potentially producing "cool" artifacts of 1-2°C in reconstructed SSTs. Nevertheless, the Sr/Ca ratio of seawater should remain sufficiently stable during interglacial sealevel high-stands to provide paleo-SSTs reliable to ±0.5°C.

Paleotemperature estimates from the Sr/Ca ratio of corals from the Caribbean and western Pacific indicate that tropical SSTs were 5-6°C cooler than today during the late-stages of the last glacial maximum (LGM) and early stages of the deglaciation (Guilderson et al. 1994; Beck et al. 1997; Figure 10, top panel) and during the penultimate deglaciation (McCulloch et al., 1999). Even allowing for a potential overestimate of the cooling due to changed oceanic Sr/Ca, these early results suggest that the envelope of potential SST change in the tropics may be larger than previously thought (CLIMAP 1976). Paleoclimate data for temperate and polar regions suggest that the ensuing Holocene climate may have been complex, with abrupt alternation between cool and warm periods at high latitudes and substantial hydrologic variability at low to mid-latitudes (Sirocko et al. 1993; Fisher et al. 1995; Lamb et al. 1995; O'Brien et al. 1995; Overpeck 1996; Alley et al. 1997; Stager and Mayewski 1997; Woodhouse and Overpeck 1998). The global climatic expression of these events, and the potential role of the tropics in their forcing, remains unclear and needs to be investigated. Key time-slices for exploring potentially rapid cooling and warming events in the tropics include the early part of the deglaciation (ca 14 ka), the Younger Dryas (10.5 ka ^{14}C yrs), the 8.2 ka cooling (Alley et al. 1997), the mid-Holocene (ca 5 to 7 ka; Lamb et al. 1995), the beginning of the Medieval Warm Epoch (ca 1000 to 1300 AD; Keigwin 1996), the Little Ice Age (ca 1500 to 1900 AD; Bradley and Jones 1993). High-resolution records from fossil corals will allow us to check the global extent of these events and the response or involvement of important climate systems such as the ENSO and monsoon.

Fossil coral paleotemperature data could also shed light on the debate about self-regulation of SSTs in the tropical warm pool regions. Previous studies have suggested that the long-term mean SST in the tropics cannot warm beyond about 29.5°C because of negative feedbacks in the radiation balance of the surface-ocean and atmosphere (Ramanathan et al. 1989; Ramanathan and Collins 1993; Waliser and Graham 1993). Coral SST reconstructions from periods when the earth may have been warmer than today could provide "hard evidence" on whether or not this apparent SST maximum can be exceeded. Key time-slices that could shed light on this important question might include the last interglacial (125 ka), the mid-Holocene "climatic optimum" (8 to 5 ka), and perhaps the Medieval Warm Epoch (ca 1000 to 1300 AD).

In addition to their use as ocean thermometers, correlations between the ratios of coral Sr/Ca (Beck et al. 1992), U/Ca (Shen and Dunbar 1995; Min et al. 1995), Mg/Ca (Mitsuguchi et al. 1996) and $\delta^{18}O$ may also make it possible to determine sea-surface $\delta^{18}O$, by removal of the temperature component of the coral $\delta^{18}O$ signal (Figure 11). Maps of sea-surface $\delta^{18}O$ could be produced to estimate variations in the volume of the planetary ice caps. If the strong correlation between seawater $\delta^{18}O$ and salinity holds through time (Rohling and Bigg 1998), it may be possible to produce maps of sea surface salinity that can be used to track changes in water balance over the tropical oceans (c.f. Gagan et al. 1998) as well as varying surface circulation patterns.

Such records are important, particularly for periods when the tropics may have been warmer than today. For instance, recent work has shown that even a small increase in tropical SST (on the order of 0.5°C) leads to a marked increase in oceanic evaporation and precipitable water in the atmosphere, both on the order of 20% (Flohn et al. 1990). Model simulations show that the tropical hydrological cycle and latitudinal gradients in SST may drive changes in the mid-latitude atmospheric circulation (Rind 1998). Coral records of the distant past could yield new insights into the links between the hydrological cycle and tropical SSTs and the degree to which water vapor in the tropics may contribute to the recent warming trend.

Figure 11 shows an example of changed tropical ocean mean temperatures and variability reconstructed from a Great Barrier Reef coral. A 12-year coral record from 5,350 ^{14}C years ago provides evidence that relative to today, background SSTs were warmer by about 1.2°C and that continental runoff was much less variable (Gagan et al. 1998). The pattern of cooler SSTs and reduced runoff associated with ENSO anomalies in this region today is not seen in any portion of this record. These data, although preliminary, are consistent with archeological evidence in Peru (Sandweiss et al. 1996) and lake sediment data from Ecuador (Rodbell et al, 1999) suggesting a very different pattern of ENSO influence prior to 5,000 years ago. Pollen data from Australia also support this interpretation; taxa adapted to the intermittent drought associated with the modern ENSO today are not present before about 5,000 yr BP (Shulmeister and Lees 1995; McGlone et al. 1992). On longer timescales, coral data from the raised reef terraces of Papua New Guinea has been used to investigate changes in the ENSO system over a glacial-interglacial cycle (Tudhope et al., 2001; Figure 12). The results of this study suggest that ENSO has existed for at least the past 130 ka, but that it has varied significantly in strength, with the modern ENSO stronger than previous glacial as well as interglacial times. Although the data are sparse, they are consistent with a dual control on ENSO strength, consisting of an element related to the precession cycle of orbital forcing (Clement et al, 1999, 2000) and the dampening of ENSO during cool glacial conditions. Given the major societal, economic and ecological consequences of severe ENSO events, and with the imminent prospect of future greenhouse warming, further coral data are urgently needed to assess this inferred sensitivity of ENSO to changes in global climatic boundary conditions.

Submerged coral drilling may also provide independent constraints on the processes responsible for glacial reduction in atmospheric pCO_2 as inferred from geochemical determinations of planktonic foraminifera (Archer et al., 2000; Sigman and Boyle, 2000). First, direct estimates of ventilation rates and pre-formed nutrients in the high-latitude surface oceans can be obtained from deep-sea corals (although such coral deposits, which occur in several hundred to thousand meters water depth, would require different sampling strategies to most of the shallow-water reef-building corals discussed elsewhere in this document). Adkins et al. [1998] combined U-Th dating, radiocarbon analyses, and Cd/Ca measurements of the benthic D. cristagalli to determine a rapid shift in the ventilation rate of the North Atlantic upper deep water. Similar observations can be made from other locations on different timescales, testing these initial hypotheses and evaluating proposed impacts from high-latitude sites [see Stephens and Keeling, 2000]. Second, paired shallow-water coral-planktonic geochemical analyses from low-latitudes will better constrain potential geochemical artifacts proposed by Rickaby and Elderfield [1999] and Elderfield and Rickaby [2000]. Because shallow-water corals calcify at restricted depths, exhibit no temperature-dependent uptake for several trace and minor elements [e.g., Shen et al., 1987], and contain discrete time intervals, coral analyses will test several previous results from the Southern Ocean. Third, shallow-water coral analyses may provide direct estimates of subtropical and tropical nutrient inventories during the Last Glacial Maximum. General circulation model (GCM) experiments have shown significant differences in the nutrient status of the glacial tropical and subtropical oceans. For example, the HAMOCC2 GCM experiments of Archer et al. [2000] have shown a two-fold increase in sea surface [NO_3^-] for the western Pacific warm pool, whereas the +50% [NO_3^-] glacial model predicts a four-fold increase in sea surface [NO_3^-]. Although such model experiments represent limit cases, the nutrient inventories of the glacial tropical/subtropical surface oceans must be better constrained via trace element and stable isotope proxies. The results of Elderfield and Rickaby [2000] question the role of Southern Ocean nutrient utilization contributing to the 80 to 90 μatm glacial reduction in atmospheric pCO_2; submerged coral drilling offers an innovative means to address these questions.

In summary, chronologically accurate, high-resolution, multivariate data sets extracted from fossil corals offer the promise of answering questions about tropical climates that cannot be answered in any other way. Although some fossil coral material may be accessed on land by sampling tectonically uplifted reefs, the geographic spread of such sites is limited, the time periods which may be sampled are restricted, and the problems of sub-aerial diagenesis often preclude the extraction of paleoclimatic records. Therefore, submerged coral drilling is urgently required to access pristine (unaltered) material spanning a wide range of late Quaternary time periods from a network of tropical localities. This network of sites should be selected to monitor specific key aspects of the tropical climate system (e.g., the Pacific ENSO; Indian Monsoon, Atlantic dipole), and will involve selecting sites to reconstruct changes in SST, zonal and meridional SST gradients and hydrological balance in all three tropical Oceans.

2.3 Quaternary Sealevel History

2.3.1 Tectonic Considerations

Every area of the world is affected by tectonic mechanisms of one sort or another: hydro isostasy, thermal subsidence, trench outer-rise elastic uplift, and mantle-plume superswells are only a few of the many tectonic mechanisms affecting reefs. Consequently, no coral reef study can escape the need for an understanding of the tectonic setting and possible tectonic influences on paleosealevel or paleoceanographic coral data sets. All sealevel histories are "relative" and none is likely to be an unadulterated reflection of ice volume or mean sealevel change.

The most geographically widespread tectonic mechanism affecting local relative sealevel histories is the global hydroisostatic adjustments controlled by the transfer of water mass between ice sheets and ocean (Peltier, 1998; Stirling et al., 1998). As a result, hydroisostatic models are perhaps the most helpful tools with which to predict the general shape of local sealevel curves, though the details of such models remain controversial and, indeed, are the subject of ongoing research (Peltier, 1998). Our improved understanding of the geographic variability of relative sealevel records for the Holocene exemplifies how hydroisostatic modeling has both benefited from and contributed to our understanding of the reef record of sealevel change (Fleming et al., 1998; Peltier, 1998). Hydroisostasy has influenced not only LGM to present sealevel and reefs, but those of every other age as well, including the marine isotope stage 5 highstands, all lowstands, and every level between. A wide array of tectonic processes are superimposed on this global hydroisostasy including 1) lithospheric subsidence (e.g., Parsons and Sclater, 1977), 2) trench and volcano outer-rise flexure (Dubois et al., 1977; McNutt and Menard, 1978; Taylor et al., 1994; Grigg, 1997), 3) a wide variety of arc-system tectonics (e.g., Taylor, 1992; Cloos, 1993; Chen et al., 1995; Mann et al., 1998), 4) rift tectonics, mid-plate superswells (McNutt, 1998), and 5) hotspot volcanism (Watts and Brink, 1989; Grigg, 1997).

To reconstruct a nearly pure sealevel record it may seem essential to avoid practically all types of vertical tectonism. While vertical tectonic displacement is a potential source of error in paleosealevel records, to avoid all vertical tectonism when selecting drilling sites would greatly limit opportunities. What's more, vertical tectonics can produce a coral record that is far more complete and accessible than records from more stable locations. The key is to quantify the contribution of tectonics to the local relative sealevel history and to recognize how the reef record has been influenced (e.g. Neumann and Macintyre, 1985).

In the absence of significant tectonic displacement, sealevel rises and falls repeatedly over the same vertical interval. Under such conditions, normal reef growth usually produces a vertical reef wall with nominal substrate on which subsequent reefs can grow as sealevel continues to fluctuate. Classic oceanic atolls usually have forereef slopes that plunge nearly vertically for hundreds or even thousands of meters. They offer the advantage of very predictable slow subsidence that makes space for interglacial high sealevels to flood their surfaces and build vertically stacked reef sequences. Atoll settings have proven particularly well suited to recover highest interglacial reef sequences (e.g., Quinn, 1991) via traditional vertical drilling. Inclined drilling on atolls permits access to both interglacial and glacial reef sequences, as documented at Mururoa by Camoin et al. (2001).

In contrast, rapidly subsiding reefs in tectonically active locations create much more growing space for coral reefs during time intervals that are poorly represented elsewhere. One example is Hawaii (Big Island) with subsidence rates of ~2.6 mm/yr related to loading by the growing volcanic mass (Ludwig et al., 1991). The result has been a series of reefs grown near lowstands going from shallow water down to ~1600 m depth. Another example is the drowned reefs of Huon Gulf, Papua New Guinea, that are rapidly subsiding as they approach the New Britain trench subduction boundary (Galewsky et al., 1996). Such subsiding reefs may contain surprisingly well-preserved coral records back to 10^6 yr or older because they have been less exposed to meteoric diagenesis (e.g., Quinn et al., 1994; Taylor et al., 1994; Galewsky et al., 1996).

Tectonic uplift may also offer advantages in the search for records of paleosealevel and climate. Uplift continuously provides fresh substrate at the base of reef systems that transgress and regress with fluctuating sealevel. Such substrate arrives in the photic zone reef-free and, typically, gently sloping. As a result, Barbados, Papua New Guinea, Vanuatu, and the Solomon Islands each have a suitable substrate on which reefs could grow during rising sealevel and be drilled successfully (Fairbanks, 1989; Edwards et al., 1993; Cabioch et al., 1998).

How, if we seek coral samples from tectonically active regions, can we compensate for vertical displacements? Fortunately, tools are available with which to document regional tectonics, predict reef morphostratigraphy, and correct coral reef sealevel records. Geologic setting, coastal geomorphology, and reef morphology indicate fairly dependably whether a reef is subsiding or uplifting (e.g., Ludwig et al., 1991; Mann et al., 1998). In a more quantitative mode, accepted elements of paleosealevel history, such as the height of sea level during the mid- to late-Holocene, provide constraints on tectonic history and provide datum levels against which to measure vertical tectonic movements. Reefs formed during the last interglacial period provide a prime example. It is generally accepted that during that period sealevel reached about 6 m higher than at present based on the heights of shorelines from localities around the world that are believed to have been tectonically stable (Veeh, 1966; Bloom et al., 1974). Where this shoreline is clearly identified then a mean rate of vertical tectonic displacement is easy to calculate.

In summary, the keys to successful coral drilling are to understand: 1) the tectonic setting and history of each potential drill site, 2) how vertical tectonic movement may affect the sealevel record and whether corrections are possible, and 3) how tectonics influence reef morphostratigraphy.

2.3.2 Coral Sealevel Records

Compilations of local sealevel curves (Pirazzoli 1991) and numerical models of post-glacial isostatic readjustments (Lambeck 1993; Peltier 1994, 1998) demonstrate that local sealevel histories varied considerably around the world in response to ice-sheet unloading and to redistribution of water masses in the global ocean. Reconstructing the last deglaciation at many sites around the globe is thus crucial to obtaining quantitative constraints on the geophysical models of the volumes and deglacial melting rates of individual ice sheets, which partly covered North America and Europe during the LGM (Peltier, 1998). In particular, new records may help to resolve the controversy about the ice sheet sources of MWP-1A which vary according to authors: from primarily the Laurentide (Peltier, 1994; Fairbanks et al., 1992), from the Fennoscandian ice sheet (Lindstrom and MacAyeal, 1993) and from Antarctica (Clark et al., 1996).

Sites located far away from glaciated regions ("far field") are needed to constrain model estimates of the eustatic changes (Fleming et al., 1998) and to complement the information obtained for Barbados. It is also essential to select and study other reefs characterized by vertical tectonic movements that are small or regular within the investigated time span.

Only three deglacial coral reef records have been accurately dated for times reaching the Holocene-Pleistocene boundary (Figure 10): at Barbados between 19,000 and 8000 cal yr. BP (Fairbanks 1989; Fairbanks 1990); at Huon Peninsula, Papua New-Guinea, between 13,000 and 6000 cal yr BP (Chappell and Polach 1991; Edwards et al., 1993), and at Tahiti between 13,800 and 3000 cal. yr BP (Bard et al., 1996).

So far, the Barbados curve is the only one to encompass the whole deglaciation as it is based on offshore drilling of the reef crest species *Acropora palmata*. The Barbados record suggests that the last deglaciation is characterized by two brief periods of accelerated melting (i.e., meltwater pulse, MWP) superimposed on a smooth and continuous rise of sealevel. These two meltwater pulses, MWP-1A and MWP-1B centered at 14,000 yr BP and 11,300 cal yr BP, respectively, are thought to correspond to massive inputs of freshwater derived from melting continental ice (Fairbanks et al., 1992). However, there are still debates concerning the general pattern of sealevel rise during the last deglaciation events, including the amplitude of the maximum lowstand during the Last Glacial Maximum (Peltier 1998; Fleming et al. 1998) and the occurrence of periods of accelerated sealevel rise (Okuno and Nakada 1999). Indeed, the Barbados sealevel curve was obtained from three separate drowned reefs. Macintyre (1972) mapped the two deeper reefs at Barbados and throughout most of the Caribbean islands, interpreting them as global still stands during the last deglacial. Fairbanks (1989; 1990) reinterpreted Macintyre's (1972) still-stand model and estimated that rates of sealevel rise reached 5 to 9 cm per year during the melt water pulses, drowning the Caribbean reefs, and reefs world-wide, by far exceeding the maximum growth rate of any constructional coral reef framework. The presence of MWP-1B at Tahiti is questionable and it is also puzzling that the sealevel jump observed in New Guinea is delayed by several centuries when compared to MWP-1B observed at Barbados. Locker et al. (1996) have proposed additional sealevel steps during the early part of the deglaciation between 18,000 and 16,000 cal yr BP.

Glacial sealevels before the LGM are even more controversial and even less well constrained. It would be extremely important to evaluate the average sealevel during that time period and to determine if rapid sealevel changes occurred in synchrony with climatic fluctuations such as Heinrich events and/or Dansgaard-Oeschger cycles. Only three Barbados glacial samples were recovered by offshore drilling and dated by TIMS (Fairbanks, 1990; Bard et al., 1990b). By contrast, numerous samples are available from the lowest terraces at Papua New Guinea that correspond chronologically to isotope stage 3 (Chappell et al. 1996). This favorable situation is due to the rather high tectonic uplift rate that allows these low sealevel reefs to be emerged today. The disadvantages of these samples are that they have been subjected to meteoric water alteration and that a large tectonic correction is needed to reconstruct their position relative to past sealevels. Indeed, the long-term (100 kyr) average uplift rate at Huon Peninsula is around 2-3 m/kyr but there is still a debate concerning the 10-1 kyr scale fluctuations (Edwards 1995; Peltier 1995; Peltier, 1998).

2.4 Radiocarbon Calibration

Radiocarbon calibration is an important topic for at least two reasons. First, the ^{14}C dating method has been in wide use since the 1950s and should be corrected for its systematic bias. The timing and rate of paleoclimatic events described in the literature is commonly established with radiocarbon dates. These dates are only as good as the calibration used to fix their calendar ages. Second, this time-dependent bias provides crucial constraints on several geophysical, geochemical and even astrophysical phenomena (see the recent review by Bard, 1998).

For the Holocene period it has been possible to find abundant fossil trees to produce a high-resolution atmospheric $^{14}C/^{12}C$ curve by measuring ^{14}C levels in tree rings of known age. Unfortunately, it has not been possible to pursue a dendro-calibration beyond 11,900 years BP because of the scarcity of trees that grew during this time. Other types of records have been used to continue the calibration effort including annually laminated sediments, shallow corals, speleothems, and other carbonates. The carbonates can be cross-dated by high-precision dating techniques: ^{14}C by AMS (Nelson et al. 1977; Bennett et al. 1977) and $^{230}Th/^{234}U$ by TIMS (Edwards et al. 1987). Since the first paper on this topic (Bard et al., 1990), there has been a continuous increase of the data base of corals but even the latest calibration software (INTCAL98) contains a very sparse dataset for ages older than about 15 ka BP. The INTCAL 98 dataset (http://www.radiocarbon.org/Journal/v40n3/notice.html) does however include over 500 coral measurements not available in the 1993 calibration (Stuiver and Reimer, 1993; Bard et al., 1998; Burr et al., 1998).

At the 17th International Radiocarbon Conference in Jerusalem, (June, 2000) several new radiocarbon calibration datasets were presented from the Cariaco Basin (Southon et al., 2000); Lake Lisan (Stein et al., 2000) and the Bahamas (Beck et al., 2000). These and other datasets from the literature (Bishoff et al. 1994; Schramm et al. 1996; Kitagawa and van der Plicht, 1998; Vogel and Kronfeld, 1997; Voelker et al, 1998) extend the calibration back to more than 40,000 years BP. However, a marked divergence for ages older than about 20,000 calendar years BP is now observed. Collecting and analyzing new corals from this time range would serve to solve this discrepancy. Corals offer much simpler uranium-thorium systematics than do lake sediments and due to their relatively rapid growth rate, they have superior time resolution than either speleothems or varves.

It is interesting to have an historical perspective on the respective contributions of varved sediments versus coral absolute dating: all extensions of the calibration based on varves have been subsequently shown to be biased by underestimation of the true ages (the problem of "missing varves"). This has been the case for the varves from the Swedish chronology, from Soppensee in Switzerland, from Holzmaar in Germany and from annual counting of the Camp Century and Dye 3 Greenland ice cores. Drilling and collecting old coral samples is thus a crucial task for improving the calibration, as it seems difficult to rely solely on varved sediments.

2.5 Fluid Flow in Reef Sequences

Fluid flow occurs in all margin settings, including the reef environment of interest to this document. While such flow is not the principal scientific target of proposed reef drilling, it is essential to consider it for the role it may play in diagenetic alteration of the geochemical tools fundamental to this work. In addition, information gained about such flow in reef environments will contribute to a range of scientific problems, from the assessment of freshwater resources in reef environments, to understanding reef cementation and its effects on oil reservoir quality.

In general, fresh water is the major fluid that moves through the upper portions of continental margins. Current estimates indicate that 10% or more of the volume of water flowing from the continents by fluvial drainage enters the oceans as submarine discharge and this proportion is believed to be even higher in oceanic islands. The geological and biological consequences of such fresh-water flow through continental margins and its ultimate discharge into the ocean is significant - driving carbonate diagenesis; changing the hydrologic and mechanical properties of the margin; altering the local geomorphology by karstification; and providing local supplies of nutrients to the overlying waters.

Such freshwater flow has the potential to induce diagenetic alteration to geochemical proxies in corals. A key observation is that many corals exposed either to rainfall or to freshwater flow exhibit initial ($^{234}U/^{238}U$) ratios that are higher than the modern seawater value. This indicates that the corals have not remained fully closed systems and underlies the importance of performing coupled U-Th and U-Pa dating in such environments (see U-series dating section). The presence of such freshwater flow presents an increasing limitation to work on uplifted terraces. However, corals that have not been exposed to such freshwater flow generally have reliable ($^{234}U/^{238}U$) ratios and ages. Submerged coral reefs, particularly those that are actively subsiding thus minimizing the exposure of samples to freshwater flow, therefore have significant advantages for geochemical reconstructions of the past environment.

Beneath the fresh water lens, fluid-flow of saline waters occurs and varies widely depending on the morphology of the platform and the sediment type. Some modern carbonate platforms and atolls are known to have very fast flushing rates. The formation temperatures of fluids can remain close to those of the adjacent oceanic waters throughout the upper 1200 m (Swartz, 1958; Ladd et al., 1970; Aharon et al., 1987; Rougerie and Wauthy, 1990). Apparently, the interstitial waters even deep within these emergent atolls are in open communication with the ocean.

Conversely, the interiors of large carbonate platforms are sometimes associated with evolved pore-water compositions and even brines. For example, salinities of more than 200 permil are known to occur within Mesozoic carbonates of the Florida-Bahama Platform (Manheim and Horn, 1968) requiring restricted circulation. In these environments with low flow rates, study of porewater Sr isotopes (Elderfield et al., 1993) and U isotopes (Henderson et al., 1999) are able to assess the mobility of these elements and therefore the likely perturbation of paleothermometry and chronology of corals.

Many driving forces exist which may stimulate fluid flow in emergent atolls or larger carbonate platforms. These are summarized in Whitaker and Smart (1990) and include tidal forces, wave pumping, small changes in the thermocline structure, hydrostatic heads associated with fresh-water aquifers, and drainage associated with changes in sealevel.

Constraining the driving forces, pathways and rates of fluid flow is important both for its impact on the reef environment and for the possible diagenetic imprint on chemical proxies. The submerged coral terraces which are the primary objective of this document are likely to have relatively rapid, seawater flow and therefore to have experienced minimal diagenetic alteration. But modeling of possible flow regimes, coupled with additional pore-water studies and petrographic study of coral samples will be an essential part of this program to ensure the reliability of the geochemical proxies and to advance knowledge of reef fluid-flow in general.

2.6 Reef Ecology

While numerous chemical proxies in coral reef cores have been used to interpret past climate in coral reef environments, another approach to reconstructing the past is the use of ecological indicators such as indicator species and their growth rates, community diversity of contained species, taphonomic considerations and bioerosion. This approach is aided by a thorough understanding of modern coral reef ecology. The more recent the core, the more reliable is the inference, and vice-versa. It is therefore useful to investigate the modern ecology of living reefs that are juxtaposed to drilling sites and use this information to help interpret the contents of extracted cores.

Indicator species can be used to deduce core water depth, the habitat in which corals were growing and the frequency of disturbance in a given habitat. For example, robust branching acroporids are considered the most reliable recorders of water depth in both the Atlantic and the Indo-Pacific. In the Atlantic, the presence of abundant stands of *Acropora palmata* is frequently used to assign a depth of 5 m or less to the cores. In the Indo-West-Pacific, *Acropora robusta* and *Acropora danai* are similarly used. In Hawaii and the eastern-most atolls in the South Pacific, *Pocillopora meandrina* and *Pocillopora verrucosa* are indicators of shallow (1-5 m) water, high-energy environments exposed to open ocean swell. The co-occurrence of the coralline algae, *Porolithon oncodes* is corroborative of shallow water high-energy environments from the level of low tide to 3-m depth. Other species characteristic of this zone are the vermetid gastropods, *Dendropoma maximus* and *Serpulorbis annulatus*. The coralline algae, *Porolithon gardeneri* is found in an even narrower depth zone and habitat on high energy reef flats exposed to open ocean swell.

Indicator species can also be used to determine growth rates, which in turn may be a function of depth, temperature or water clarity. The most useful species are massive forms, *Porites lutea* in the Indo-Pacific, *P. lobata* in Hawaii and *Montastrea annulata* in the Caribbean Sea. All three of these species have clear annual growth rings. Growth hiatuses may be used to interpret frequency of disturbance due to bleaching or *Acanthaster* predation.

Community composition can also be interpretative of habitat. Fragile or highly branched forms are restricted to sheltered or deep environments. The co-occurrence of other shallow (coralline algae) or deep (molluscs or *Halimeda*) species can be used to distinguish lagoonal from deep-water habitats. The lack of branching forms, which are more susceptible to bleaching may indicate the frequency of disturbance due to bleaching events; perhaps even a proxy for the frequency and magnitude of El-Niño events.

Community diversity is also related to successional state. Low diversity with a high frequency of pioneer species such as *Pocillopora meandrina* is suggestive of an environment frequently disturbed by high waves. Taphonomic effects must also be taken into account in interpreting core paleoclimate. Selective preservation or bioturbation can easily alter species composition. For example, the absence of highly branched porous species of coral may be caused by their selective erosion (Scoffin, 1993).

Another useful indicator of paleoenvironment is bioerosion. Ray Highsmith has shown that the degree to which coral skeletons are bioeroded can be directly related to the primary productivity of overlying waters. Lagoons for example, which are more eutrophic than offshore waters may support similar species which show significant differences in the extent to which their skeletons are excavated by bio-eroding organisms.

Finally, community structure may change due to changes in sealevel associated with glacial cycles. During low sealevel stands, reefs may be more isolated due to lack of connectivity caused by altered or truncated current systems. Lower temperature during such events may selectively remove some species giving way to lower diversity. High stand communities would exhibit the opposite trends.

In conclusion, the use of ecological indicators to interpret paleoclimate, while somewhat qualitative, is best applied in combination with other information and data including various chemical proxies and isotope ratios. Certainly in Holocene or even Pleistocene sequences, an understanding of modern reef ecology will greatly aid in the interpretation and reconstruction of climate based on coral reef drill cores.

3 *Imaging Submerged Coral Reefs*

3.1 Introduction

Prior to commencing drilling activities into submerged coral reefs, some level of site-survey work beyond remote sensing may be necessary. This may include satellite and aircraft platform-based remote sensors to be used as reconnaissance tools. However, some form of submarine, geoacoustical remote sensing is required. The type of target and its geologic setting will dictate the choice and deployment of the most appropriate imaging tools.

The Ocean Drilling Program's requirements and procedures that govern ODP's Site Survey Panel and Safety and Pollution Prevention Panels are an appropriate model of site survey requirements of submerged coral drilling. The submerged coral drilling community, as part of the broader academic shallow-water drilling community, will eventually have to specify the requirements for site surveys. These communities will also need to develop a site survey review process that ensures that the principal investigators and proponents can realistically attain their scientific objectives, and conduct drilling in a safe and environmental friendly manner.

3.2 The Search for Drilling Targets

3.2.1 Homework Phase

Prior to conducting any fieldwork, the initial task of the principal investigator is to acquire as much information about the targets of the potential submerged coral reef drilling as possible. The amount and type of information available can be highly variable depending on the amount of previous work, if any, at a site location. Initial tasks involve acquiring and examining as much satellite and aircraft-based imagery as possible.

Satellite Imagery — There are two useful types of satellite imagery: (1) Landsat and (2) SPOT. Landsat has lower resolution (30 m pixel; 180 km by 180 km) and is less expensive than SPOT, but it can penetrate deeper into very clear water (~20 m) because of its blue band. Information about Landsat imagery can be obtained at the web site (http://edcimswww.cr.usgs.gov/pub/imswelcome/). SPOT is a French satellite system producing images with a 10-m pixel (60 km by 60 km), which can penetrate 15 m into very clear water. More technical information and prices can be obtained from Jessica GUERS, Inside Sales - Distributors, Universities & Vegetation, Phone: 703-715-3128, FAX: 703-648-1813, Email: guers@spot.com, SPOT Image Corporation, 1897 Preston White Drive, Reston, Virginia 20191 USA.

Aerial Photography — Vertical, rectified aerial photography can be obtained from local contractors. They are generally located in populated areas such as Hawaii or Florida. Resolution is dependent upon film type, flight altitude, air and water clarity, etc. In very clear water, reefs can be seen down as deep as 20 m. Some states and countries may already have an aerial photograph data bank available.

Site Survey Data — There are formal and informal data banks, which may contain high-resolution bathymetric and seismic-reflection imagery. These exist within academia, industry, and government. The best known is ODP's Site Survey Data Bank located at the Lamont Doherty Earth Observatory, which archives data submitted by proposal proponents during the proposal review phase. These data are examined by the appropriate ODP panels and are generally propriety, but may be examined with permission. Within US waters, the Bureau of Mineral Management (BLM) as well as the USGS have collected enormous data sets on certain continental shelves. Finally, individual scientists may have potentially significant and relevant data stored at their own institutions.

3.2.2 Field Work – Site Survey Phase

Fieldwork can commence once the pre-fieldwork has been done and appropriate existing data leads have been exhausted.

Navigation — First and foremost, any fieldwork will require accurate navigation obtained from the GPS system. In remote areas, with the signal no longer purposely degraded by the US Navy for security reasons (selective availability removed), horizontal position accuracy should be within several meters. Near developed coastal areas with an accompanying radio beacon broadcast of differential corrections, such as provided by the U.S. Coast Guard, differential GPS or DGPS providing sub-meter horizontal positioning accuracy can be obtained. The positioning data stream must be digitally recorded and any mature drilling proposal must produce a cruise-track map generated from these data showing the location of all geoacoustically derived data. This map(s) must be of such scale that meter-scale features seen in bathymetric maps or side-scan sonar, data can be located and individual shot points from high-resolution seismic reflection data can be found. High-resolution swath bathymetric surveys require a more accurate level of positioning accuracy, including vertical positioning and motion sensing.

Bathymetry: All drilling, but particularly shallow-water drilling (<200 m) requires accurate bathymetry over the drill targets and over surrounding areas. This provides the investigators with essential morphological data, which adds to the scientific merit of the work, but also provides essential information for drilling activity particularly dealing with concerns of safety and environment protection. Bathymetry surveys obtained using multibeam instruments provide the best information.

Side-Scan Sonar: High-resolution, side-scan sonar profiling (100 kHz/500 kHz acoustical signals), particularly in mosaic view, can provide additional textural information not seen in the multibeam imagery. Side-scan imagery will not provide bathymetry but will detect changes in bottom roughness resulting from the benthic community changes, small topographic changes below the resolution of multibeam data, and sediment grain size/composition changes. Current standards expect data to be acquired in digital form so that map mosaics can be generated.

Very High-Resolution, Seismic-Reflection Profiling*:* High-resolution, seismic-reflection profiling is required to image the subsurface and to determine the stratigraphic setting of the drilling target. Very high resolution is generally considered to be data that provide meter-scale horizontal resolution and sub-meter scale vertical resolution (Shipley and Moore, 2000). These geoacoustical devices generally operate in the 400 Hz to 6 kHz range and broadcast a range of sound frequencies. These include traditional "boomer plate" sound sources and newer chirp FM sound sources. The use of chirp sonar in reef settings has never been adequately tested. Both single-channel (SCS) or high-resolution, multichannel seismic (MCS) systems are available. However, the increased complexity and cost of high-resolution MCS data and its lower resolution, as compared to the very high resolution tools, probably do not justify its use in most submerged coral drilling site surveys. Its use would be justified in deeply submerged or drowned (>200 m water depth) targets. Logistics, resolution, penetration, and cost all factor into the best choice of seismic tools.

Some of the above mentioned tools can be deployed simultaneously to avoid needless duplication of vessel operations. The multibeam bathymetric tool can be run faster (8-10 knots vs. 4-5 knots) than the seismic reflection and side-scan sonar tools. However, an initial survey, which includes the simultaneous operation of both the multibeam and a side-scan sonar set to a swath width to more closely match the multibeam swath width would be prudent. In this manner, complete coverage of the seafloor using these two different geoacoustical tools would be obtained.

A separate seismic survey might be conducted as the closely spaced grid required of the multibeam and side-scan sonar would not be necessary for the seismic data requirements. To obtain the subsurface information, a grid of crossing lines running a high-resolution, seismic reflection system is required. From this data set, subsurface structural contour and isopach maps can be made. In reconnaissance mode, these lines should be run about 1-5 km apart. However at potential site locations, lines should be run every 200-m apart with a minimum of 10 parallel lines run in one direction and an additional 10 crossing lines run in a perpendicular direction.

3.2.3 Field Work--Bottom-Truthing Phase

Direct bottom observations through ROV-mounted TV, SCUBA, surface-lowered bottom cameras, etc. should be conducted to assess the benthic community that might be impacted by drilling or to locate large coral heads as drilling targets. Eventually, it is probable that autonomous underwater vehicles (AUV's) with geoacoustical sensors and underwater TV cameras will be available for bottom-truthing potential drill sites.

3.2.4 Post Field Work Operations

Data Processing: Data processing of the navigation and geoacoustical data is a time-consuming and expensive element of any site survey that is required to generate cruise tracks, mosaics, and map products. PI's should recognize that fact in planning and budgeting for site surveys.

Forward Seismic Modeling: Forward seismic modeling can be used to test hypotheses concerning the compositional, textural, and geometric characteristics of submerged reefs. Seismic models can include geometric models and rock-property models, as well as combinations of the two. Geometric models take a known stratigraphic geometry and examine the seismic response. For example, a model of the seismic character of downlapping flank beds could be used to more accurately identify and predict the location of the downlap surface. These types of models can be useful for ray path modeling in complex settings. Rock-property models are different in that they use a known pattern (from an impedance log, for example) as a baseline, then systematically vary parameters (e.g., porosity, mineralogy, and cementation) to modify the impedance values. This new reflection series is then convolved with the pulse, and the changes in seismic response can be related directly to changes in rock properties and used as a qualitative predictive tool. These two approaches can be merged in a geometric model run several times with different rock properties. Forward seismic modeling is used in the petroleum industry (Hart and Balch, 2000).

Seismic attribute analysis: Relations between rock properties determined from well, core, or modeling and seismic trace characteristics can be quantified using seismic attribute analysis. By directly comparing the input (rock data) and response (seismic attributes), a predictive model can be generated through use of neural networks or linear regression. Seismic attribute analysis is commonly used in the petroleum industry to predict facies or porosity (Matteucci, 1996; Russell et. al., 1997; Rankey and Mitchell, in press).

3.3 The Tools of the Trade, How They Work, and Their Cost

3.3.1 Navigation

DGPS is the best method to obtain accurate navigation information. Such a unit can be mounted and operated on a small vessel (8 m in length) and tied directly into a monitor to assist the boat operator and, of course, recorded with the incoming geoacoustical data. Larger vessels should have all of this already on board. Underwater transponder locators may be needed for greater accuracy in deeper water. A realistic assessment of the net navigational errors should be determined for planning survey objectives and reassessed for post-cruise processing. DGPS units, navigation software to provide real-time positioning for the boat operator, and a small computer are readily available for about $6k or less.

3.3.2 Multibeam

The EM 3000 sonar is a 300 kHz multi-narrow-beam sonar that generates high-resolution bathymetry and backscatter imagery. It works best in water depths of 1 m to 150 m. It generates 127 narrow beams (1.5^o X 1.5^o) and has a maximum ping rate of 25 Hz. The swath width is 135^o which equates to a seafloor coverage of ~ 4 times the water depth. The beam spacing is 0.9^o. It has a depth resolution of 1 cm and a depth accuracy of 5-cm RMS. It has a lateral resolution 20 cm and lateral accuracy of 1-m RMS. High-resolution gridding of data in shallow waters can be down to 20 cm by 20 cm and items such as the gun and turret of a tank in 10 meters of water are detectable. To compensate for boat motion (pitch, roll, yaw, and heave) a TSS POS/MV 320 system is used to determine boat motion and position. An additional GPS system is used to monitor the elevation of the vessel during survey to deal with rise and squat of vessel, and changes in sealevel due to tides and meteorological conditions.

Rapid processing of data is possible at sea using the Merlin Software on the Sun Ultra 5 acquisition and processing computer. Bathymetric maps can be made within an hour or two of survey (depending on amount of area surveyed). Several types of maps can be generated, including contours, color-fill maps, artificial illumination maps that display the data in black and white and associated shadows and bright spots from an artificial light source projected onto the data (Figure 13). Backscatter images (similar to side-scan sonar images) are also available, and are useful in characterizing the geology of the seafloor. It is a portable system that can operate on small or large vessels using a pole-mount configuration or it can be permanently fixed to the hull of a vessel. With all associated equipment it costs about $400K.

3.3.3 Side Scan Sonar

The most common systems consist of towfish with 100-500 kHz ranges in transducer frequencies (100 kHz is most common). Systems range from all analog ("old fashion"), to mixed analog/digital (analog signal from towfish travels up the cable and is converted to a digital signal by computer on ship), to mostly digital (the sonar transducer signal is digitized at the towfish and sent up the cable as a digital signal). The main difference in application is that analog cables lose signal strength over long cables in deep water (~>600 m); thus a digital signal is preferred in deep water. Normal towing speed is 2 to 5 knots. A side-scan fish towed on shorter cables is subject to sea state and ship motion problems. Longer tow cables increase navigation problems. These units cost about $100k and can be rented for about $2k/day with an operator. These costs do not include shipping, mobilization/demobilization costs and vessel operation costs. There are new systems available that are multichannel, which can be towed faster with enhanced resolution. However, these units are much more expensive than the more standard varieties.

3.3.4 Very High-Resolution, Seismic Reflection Profiling

Very high-resolution, seismic reflection profiling generally means the use of electromechanical "boomers", small sparkers, and very small (1-15 cubic inch GI air guns) as sound sources (Figures 14, 15). These generate a broad range of acoustic frequencies (300 Hz to 6Khz) and provide up to 0.2 seconds of penetration which translates to about 150 to 200 m of penetration in unconsolidated sediment. Penetration is primarily frequency-dependent with cemented sediments having higher velocity, but requiring lower frequencies to obtain penetration. There are tuned transducers such as 3.5kHz, which generate a single frequency. These have been historically used as two-dimensional bottom profilers and will produce some penetration in soft sediments, so they have been popular with paleoceanographers working in deeper waters. However, a 3.5kHz system probably would provide very little to no penetration in reefal environments. Seismic systems, such as high resolution multichannel seismic (MSC) or industry-level MSC that produce hundreds to thousands of meters of penetration are not well-matched to the scale of the submerged coral drilling, where <50m of core are commonly needed, unless deeper stratigraphic information is needed.

Resolution, both horizontal and vertical, is dependent upon the physical characteristics of the outgoing signal, the depth of the target, and the velocity (compressional wave; Vp) of the rock/sediment medium through which the signal travels. For horizontal resolution, the size of the “acoustic footprint” is determined by the size of the Fresnel zone, which is a function of Vp, two-way travel time (distance to reflection measured as time), and the dominant frequency of the outgoing signal. So a “boomer” having a dominant signal frequency of 1kHz traveling through 20 m of water will have an 8-m diameter circle as its “acoustic footprint”. This means that it cannot discriminate between several 2-m diameter head corals resting on the bottom or buried in the subsurface. Side-scan sonar, however, should be able to “see” and discriminate between these separate targets on the bottom. But, the very high-resolution seismic profiler will not be able to produce separate images of these individual targets in the subsurface.

For vertical resolution, a rule of thumb is used to calculate the minimum separation that can be imaged between separate reflecting horizons. That rule states that the minimum vertical separation that can be imaged lies between 1/8 and 1/4 of the Vp wavelength. Wavelength can be calculated from the Vp and the dominant frequency of the outgoing pulse. So, for a 3.5kHz system, the vertical resolution lies between 6-12 cm in soft sediments. For a boomer system, this range in unconsolidated sediments is 20-40 cm. In practice, these estimates for both the boomer and the 3.5 kHz are highly optimistic and are rarely ever attained. The cost of a boomer-type system is about $100k and the cost to rent one is about $2k/day not including the other charges cited above.

A newer technology called chirp sonar is now being used extensively in siliciclastic environments, but to our knowledge, there has not been extensive deployment in carbonate terraines specifically including coral reefs. This is a FM acoustic, sub-bottom profiling system that sweeps across a broad frequency band (e.g., 1 to 15 kHz), has a short pulse length resulting in maximum horizontal resolution of 25 cm but providing ~30 m of penetration in unconsolidated shelf siliciclastic sediments (Duncan et al., 2000). The transducer may also be deployed in a subtow mode that reduces sea-surface noise and motion and avoids signal loss because it does not have to travel so far through the water column.

These data are recorded and processed digitally. Compared to boomer-type systems, chirp sonar provides higher resolution, reduced noise, and reduced multiples (Figure 16). However, it remains to be seen how this system will perform in more acoustically reflective carbonate environments. A field test would be highly desirable to see if the chirp system would be viable tool in submerged coral drilling site surveys. Chirp systems offer a variety of sound sources that sweep different frequency ranges. Ones offering a lower frequency range would be best for carbonates. The system used by Duncan et al (2000) cost about $100k.

4 Geotechnical Aspects of Submerged Coral Drilling

It is clear that the science, imaging and geotechnical communities need to be better integrated if a scientific drilling program focused on coral reefs is to become a reality. However, a logical first step is to breakdown the barriers of communication between the groups. A glossary of geotechnical terms (Appendix II) was created to facilitate this integration. Words listed in the glossary are highlighted in bold in the text that follows.

4.1 Introduction

Submerged coral drilling targets have a wide range of drilling site requirements but all commonly require high quality core recovery from carbonate reefs that can be expected to alternate between competent reef limestone and completely unconsolidated carbonate sands and mud. The ability to drill and recover undisturbed samples from in situ coral heads is of paramount importance. Indeed, one school of thought in submerged reef drilling envisages a research strategy that targets only the coral heads without concern for recovery of the unconsolidated material that likely surrounds the coral heads. However, the other school of thought in submerged reef drilling insists that critical information required to faithfully reconstruct the environment of deposition and water depth of the reef sequence is contained in the sediments surrounding the coral heads; therefore all material needs to be recovered. While the scientific value of recovering reefal sediments may still be debated, good drilling practice should attempt to recover this material if only to improve the stability of the hole to enable further quick efficient drilling.

Another scientific philosophical discussion that would influence the drilling approach concerned the recovery of coral heads by drilling several shallow holes requiring quick drill rig set ups compared to drilling fewer deeper holes. Both types of operations are feasible but a significant influence could be water depths. For example, a small shallow-water operation is more likely to be mobile between closely spaced sites than a blue-water ship operation where site set up takes longer and is less precisely controlled. The technology exists or could be developed and applied to service all these drilling requirements.

4.2 Conventional Geotechnical Operations

Workshop participants with the appropriate background in the geotechnical aspects of shallow-water drilling put together a summary of conventional, state-of-the-practice, geotechnical tools and investigations. This section provides background information pertaining to vessels, portable drill rigs, **riser** versus non-riser drilling, *in situ* testing and coring equipment, heave compensation, **seafloor templates**, re-entry capabilities, and cantilever versus **moonpool**/**centerwell** deployment schemes.

Tables 4.1, 4.2, 4.3, 4.4 and 4.5 provide a detailed summation of the types and sizes of the various **drill-pipe configurations**, **flush-joint casing**, **diamond coring systems,** and sediment sampling and coring options currently available for geotechnical operations. Table 4.5 summarizes the attributes of the 17 potential platforms available for conducting geotechnical sampling and coring operations. Table 4.6 summarizes the attributes of 3 classes of drilling options available for shallow-water, submerged coral drilling.

4.2.1 Vessels

Most conventional shallow-water geotechnical operations are conducted from oil-field supply vessels in relatively calm sea states such as those found in the Gulf of Mexico, Bay of Campece, Beaufort Sea and many parts of West Africa and Southeast Asia. Several geotechnical contractors operate many such vessels with portable rigs mobilized onboard. Most of these vessels are **four-point anchored** vessels with **moonpools** varying from 24" to 60" (0.6-1.52 m) diameter. These vessels typically have a set of large winches and anchors that are capable of holding the vessel on location during drilling operations. These ships are normally used in water depths < 500 m unless special provisions are made for anchoring using pre-installed **pennants**/anchoring schemes.

A much larger and dedicated vessel with a fixed derrick is used for operations in the rougher North Sea or deep-water locations. Examples of these types of dedicated geotechnical vessels are the M/V *Bucentaur* and M/V *Norskald*. These vessels have large **centerwells** on the order of 10-ft (3 m) square. This size of **centerwell** is required for the large reaction mass typically needed for in situ testing work or use of **piggyback coring systems** (i.e., rock coring through the large diameter **API** drill pipe).

These vessels are **dynamically positioned** and have fixed derricks ranging in height from 85-ft (26 m) to over 100-ft (30 m) tall. A depth capability for these vessels (water depth plus depth of penetration) is normally less than 3280-ft (1000 m) with steel pipe. Special equipment can be utilized such as lightweight aluminum drill pipe or air cans to increase this working depth. These adaptations can increase the depth capabilities to ~5900-6900' (1800-2100 m) depending upon the specific vessel. Some of the dynamic-positioned geotechnical vessels are also set up to with a **four-point anchoring system** for holding location in shallow water.

4.2.2 Portable Drill Rigs

Skid-mounted drilling rigs have been used on offshore operations for the past 30 years. These rigs are popular due their ease of portability. **Mobilization** is relatively quick and simple on vessels of opportunity, which have adequate anchoring systems and a **moonpool**. Typical skid-mounted rigs include those normally used for mining operations, both rotary and diamond coring. Pipe rotation and a kelly drive and rotary table handles advancement for these rigs. Depth ratings vary based on the actual type of derrick and number of lines used on the hoisting block. For instance, a Failing 2000 is rated for 2500 ft (762 m) with 2 7/8" drill pipe. However, using a larger drill pipe, such as 4” or 5", to accommodate *in situ* testing tools and larger samples, reduces the operating limits. The working limit of a Failing 2000 system becomes less than 2000' (600 m) of water, without special pipe or other equipment. Likewise, a Failing 1500 with 3" or 4" pipe is limited to between 800 to 1000 ft (250 to 300 m) of water, respectively. There are numerous other pieces of equipment, which are required based on the type of soil or geologic investigation being performed, besides the rig itself. This “mud boat” type of operation has served its purpose very well for sedimentary sampling in locations such as the Gulf of Mexico.

With the advent of more sophisticated offshore drilling platforms and deep-water operations these types of portable rigs begin to be replaced with a more versatile **top drive** type of drill rig. Fugro was instrumental in working with Wirth in developing a new generation of portable drilling rigs that had an **active heave compensator** included in its derrick. These rigs use a hollow spindle top drive. Having a hole through the top drive allowed an increase in versatility of sampling and *in situ* testing tools that could be deployed. This rig was designed so that it could be **cantilevered** over the side of a vessel and that all pipe-handling operations would be inward. This eliminates the need of a special work platform required over the side of the vessel for drilling rigs such as the Failing 1500. This rig was also designed with the forethought of being sized so that it could be easily shipped and transported via standard sea freight containers.

Seacore has also developed a portable rig named the Seacore Marine Drill C-100. It has similar depth rating to that of a Failing 3000. However, it has the added features of an open **top-drive swivel**. A major advantage of this system is that it also was designed around 40-ft (12.2 m) sea freight containers. The unit is self-contained and only requires the assistance of a 70-ton crane with a boom height of 100-ft (30 m) during the initial mobilization. Because of the size of this rig it must be operated over a **centerwell**. Minimum **centerwell** size required is 6.5' x 6.5' (2 x 2 m). Seacore also pioneered a unique solution to rock coring through the large diameter **API drill pipe**. This solution uses a thin-wall, **wireline** coring system with a small mining rig. This technique has been called “**piggyback**” coring. It is achieved by mounting a smaller mineral/mining type drill on top of the **heave-compensated top drive**. The small mining rods are then lowered through the 5" **API drill pipe** that has previously drilled and sampled the softer soils. Once lowered to the bottom of the hole, the mining string is then rotated out the bottom of the **API bit** to begin diamond coring. The **API** string acts as a **riser** and is held at the seafloor via hydraulic clamps attached to the **seafloor template**.

Geo Drilling has developed a containerized drilling system, CDS, based on a standard mining diamond coring rig. It comprises 5-m heave compensation, a seabed frame which make it possible to re-enter the hole, and a plastic **riser**. The total weight is less than 100 ton and the typical vessel used for deployment of the CDS system should be longer than 200-ft with **dynamic positioning** or a **four-point anchoring** system. The drilling is performed either through a **moonpool** or **cantilevered** over the side or at the stern. In addition to **diamond coring**, **push sampling**, **piston coring**, **punch coring** and **percussion coring** can be performed. The core diameter varies from 33 (BQ) to 83 (PQ) mm with HQ, ~60 mm, as the most common size. The total drilling capacity is in the order of 500 to 1500 m, depending of the selected core diameter.

In 2000, DOSECC (Drilling, Observation and Sampling of the Earth's Continental Crust, Inc.), in a joint venture with the International Continental Scientific Drilling Program (ICDP) developed the GLAD (Global Lake Drilling) 800 system. This consists of a conventional **diamond-coring rig** mounted on a barge. It is capable of collecting ODP-size core to a total depth of 800 m. The system maintains position through **four-point anchoring** and drills through a **riser**. This drilling system was specifically developed to collect samples in modern lakes for climate change investigations. It was initially deployed in the Great Salt Lake and Bear Lake in Utah where it collected a total of over 650-m of core in multiple holes.

4.2.3 Riser versus Non-Riser

A **riser** is a length of casing that extends from the sediment through the water column. The drilling **rods** or pipe are then inserted through the **riser**. A **riser** in geotechnical drilling operations is usually only required to support the **drill pipe** or tubing string when **tool joints** or connecting **rods** are not strong enough to accomplish this purpose themselves. A riser is used occasionally when drilling mud is required for recirculation during shallow-water operations. Most rotary shouldered connections such as those found on 3”, 4”, 5" and larger drill pipe utilize **upset** API type connections that can be operated without risers. Attempting to core with slim-line mining rods without supporting the connections through the water column can be disastrous. The connections used on most mining-type strings or slim-line rods will break unless they are laterally supported. The problem is compounded without a good heave compensation system. Therefore, if slim-line diamond coring is attempted using thin **kerf** bits from a vessel, a **riser** of some sort must be employed. The **riser** must also be held in tension or as straight as possible to reduce torque while the inner string is rotated at a high speed. Most mining systems are designed to use the previous coring string to support a smaller coring string. Thus a nested casing arrangement is developed. It must also be noted that unless the **riser** is the correctly sized for the coring string to protect the thin-walled mining string, problems can still develop. Also, unless the proper tensioning equipment is provided for the **riser**, binding and connection failures can still occur.

4.2.4 In Situ Testing and Coring Equipment

The introduction of *in situ* testing equipment adds an additional degree of complexity to the drilling operation. Typical *in situ* testing includes cone penetrometers, remote vanes, and **piston samplers** all of which are pushed into the ground at a controlled rate of speed. These tools can provide very high quality data in mapping out stratigraphy. The harder the material, the more difficult these tests become from the standpoints of reaction mass size, strength of materials, and data collection. The weight of the reaction mass to compensate for the forces that must be overcome to push a tool into normally consolidated material typically is between 7 to 10 tons.

There is an upper limit of thrust or push that should not be exceeded before potential damage can occur to the tools. It is not uncommon to bend a cone rod or sampler when encountering a hard strata or cobbles/gravel. Bending of such a tool outside the bit may result in the whole drill string having to be withdrawn and pulled back to the ship to retrieve the bent or broken tool. This is a time-consuming operation and one that can result in down time for the vessel but also for the equipment as well. Once this harder material is encountered and the tools “max out” as it is called, other sampling equipment and hardware should be deployed.

Conventional marine coring equipment using roller cone, polycrystalline diamond cutter (PDC’s), or diamond bits can be substituted to obtain cores. Another means for sampling if over consolidated clays or compacted material are expected is the use of thick-walled taper tubes. These can be driven into the formation using a down-hole hammer or by using the weight of the drill string to push the sampler into the formation. Such samplers are normally only employed when everything else fails. **Wireline** hammers are typically limited to water depths less 1640 ft (500 m) due to the loss of the **wireline** sensitivity.

McClelland Engineers (now merged with Fugro) developed an *in situ* sampling and testing system named the Dolphin. The principal advantage of the Dolphin system is that it does not require an umbilical as most other *in situ* tools had before. Therefore, its operation is much more expedient for deep-water application and requires less support equipment than a conventional set up. The Dolphin uses a remote memory unit (RMU) to record data. The Dolphin can be configured into several types of tools depending upon the specific type of test required including 1) Cone Penetrometer (CPT), 2) Piezocone Penetrometer (PCPT), 3) Remote Vane Shear (RV), 4) Temperature probe (TP), 5) Piezoprobe (PP), 6) Piston sampler, and 7) Piston Liner sampler.

The configured tool is pre-programmed on deck then is allowed to freefall down the pipe and land into the thruster unit. The drill string is then clamped to the seafloor reaction mass via a hydraulic jaw system operated through a hydraulic umbilical. Increasing the mud pressure in the drill pipe then starts the test. Once a specific pressure is reached and held, the pressure is then bled off, and the tool is recovered with an **wireline**-**overshot** assembly. Once back on the deck, the tool is interrogated and the data transferred into a personal computer. The selection of reaction mass type is dependent upon the **moonpool** configuration of the vessel.

4.2.5 Heave Compensation

Heave compensation is standard equipment for all offshore geotechnical investigations. As mentioned earlier, requirements for high-quality samples and in situ testing precipitated the introduction of heave compensators offshore. Passive and active are the two main types of compensators available. The **passive heave compensator** attempts to hold a constant set weight using a pre-selected amount of compressed air introduced into a cylinder arrangement. The **active heave compensator** uses a similar cylinder arrangement, but is usually fed a real-time signal from an accelerometer, pressure sensor or similar device to actively inform the cylinder to either increase or decrease the pressure to maintain a constant weight on bit. These types of compensators are usually in line with the derrick and are connected above the **top drive**.

Heave compensators were added to these types of rigs in the late 1970's using **guideline tensioners**. The **guideline tensioner** is usually a freestanding piece of equipment located next to the rig that runs one strand of the draw works cable through a series of shieves. The number of shieves dictates the amount of movement that the rig can compensate against. While this set up is not ideal due to the large amount of friction developed in the sheaves, it has allowed **diamond coring** to be accomplished in relatively benign environments. The main purpose for the addition of this type of **heave compensation** was not for drilling, but the addition of *in situ* testing and the need to isolate the drill string motion during a test.

Heave compensation has also been attempted using a bumper sub. A bumper sub is a telescoping splined joint placed at an appropriate location in the drill string. The location is chosen based on how much weight on bit is required for drilling or coring. The remainder of the drill string is held in tension by allowing the bumper sub to be held at approximate mid stroke so that any heave is removed up to half the length of the bumper sub.

Continuous coring offshore has also increased the need of the **heave compensator** to accurately keep a constant weight on the bit. **Diamond coring** is especially sensitive to any changes in weight on bit. Even with as little as several hundred pounds of change in weight on bit, the core can jam or cause the bit itself to become damaged. This is especially true on small cores less than HQ sizes (2.5" OD). Therefore, it is usually a given that the better the heave compensation system on a rig the better quality of sample or data will be obtained.

The **passive heave compensators** have also been utilized in conjunction with a seafloor reaction mass. This large mass has a set of hydraulic jaws that serve as a clamping device. The reaction mass is installed upon the seafloor prior to the start of the soil investigation. It can be lowered independently on heavy lift lines or with the drill string itself. The type of reaction mass selected is largely dependent upon the moonpool/center-well arrangement of the vessel.

4.2.6 Seafloor Reaction Mass

In order to perform an *in situ* test such as cone penetrometer, remote vane or a high quality **piston sample**, the drill string must be isolated from any motion. Hydraulic jaws on the reaction mass are use to clamp onto the drill pipe to provide a reaction for the compensator to compensate against. Once the test is completed, the jaws are released. The sample or tool is recovered via **wireline** and then drilling is resumed to the next interval before the process is repeated. It should be noted that the hydraulic jaws require a set of hydraulic lines run from the surface to the jaws on the seafloor reaction mass. Precautions must be taken to protect the hydraulic lines from getting wrapped around the drill string. These hydraulic lines also require another piece of deck equipment to keep the umbilical hoses spooled and tensioned.

Not only is a seafloor reaction mass required for *in situ* testing but additional **mobilization** time is needed to install it and additional personnel are usually needed to operate and maintain the equipment. The seafloor reaction mass is basically a large clump weight that provides a reaction force for an *in situ* tool to be pushed into the formation. Reaction masses can be as simple as a set of hydraulic clamps or as sophisticated as including a subsea power pack and pan and tilt cameras.

<u>Heavy Lift Line Template</u> - The lift line type of reaction mass is normally associated with the large North Sea vessels where **centerwells** of 6.5 to 10 ft (2 to 3 m) square are typical. Templates of this size are due to the heavily overconsolidated nature of the soil in parts of the North Sea and the need to have more weight to react against. These reaction masses are lowered independently of the drill string with large diameter cables spooling off a compensated winch. One major advantage of the heavy lift line type reaction mass is that borehole reentry can be easily accomplished.

<u>Slim Line Reaction Mass</u> - The slim line reaction mass was developed specifically for vessels that have a small diameter **moonpool**, such as those vessels found in the Gulf of Mexico. This type reaction mass is not required to be as heavy since this type of operation

using these "mud boats" are in normally consolidated materials. This reaction mass is lowered via the drill string. Once the mass is resting on the seafloor, the drill pipe is continually lowered until it passes out the bottom of the reaction mass. Upon borehole termination, the drill pipe is retrieved and the reaction mass is picked up with it once the bit clears the seafloor. The slim line reaction is normally required to be keel hauled at a dock during the vessel **mobilization**. A set of locks installed on the vessels deck hold the reaction mass during transit.

Hybrid - A hybrid type of reaction mass, developed by Fugro, is compact like the slim line version but can be deployed on lift lines. This allows the drill string to be removed if required, in order to change the bit or **bottom hole assembly** if harder materials are encountered. This reaction mass requires a **moonpool** of at least 5-ft (1.5 m) diameter and still requires the use of a winch to raise and lower the template.

4.2.7 Re-Entry Capabilities

Re-entry capabilities allow the borehole to be re-entered after it has been initiated in case a bit must be changed or a different type of drilling system is required prior to moving off location. Re-entry in this case should not be confused with re-entry where a permanent cone or other type seafloor device is left for a future visit to the same borehole. Typical re-entry for geotechnical borings allows the bit to be guided back into the existing borehole via a set of lift lines attached to a seafloor reaction mass or through a compensated riser system. The hybrid reaction mass can be lowered with a guideline system through a **moonpool**, if the **moonpool** dimension is at least 5-ft (1.5 m) and its shape may be either square of circular.

Slim line **risers** are typically run with some sort of seafloor mass or frame so that they can be tensioned when in operation. This kind of **riser** is used when a conventional mining type string is deployed. The riser basically provides the support for the weaker mining string connections. Drilling mud is usually not re-circulated with this type of **riser**. However, if part of the **riser** is jetted or washed into the seafloor so that a seal is formed it may allow the drilling mud and cuttings to be returned to the vessel. **Risers** of this sort are hung underneath the drill rig so as not to interfere with the normal coring/drilling operations. For this type of operation to be successful the rig normally must be elevated so that there is sufficient room underneath the rig for a diverter to allow the cuttings to gravity flow into a settling basin before being recycled. Also the **riser** must be compensated or use a long **slip-joint** type of arrangement.

4.2.8 Cantilever versus Moonpool Deployment Schemes

Most vessels that perform core-drilling operations usually have a **centerwell**. This allows the rig to be placed firmly on the deck of the vessel so that heave can be minimized and drill pipe handled more safely. Some drill rigs can be **cantilevered** over the side or stern of a vessel if no **moonpool** is available. This position is less desirable since vessel motion is accentuated at the extreme edges. By operating through a **moonpool**, the equipment is also less susceptible to the vessel changing headings should weather conditions dictate.

Based on a rig's configuration, a work platform over the side of the vessel may be required to support the workers and possibly the weight of the drill string. This is the least desirable situation especially should the pipe become stuck. A structurally sound design of this work platform is critical as water depths increase since the entire weight of the drill string will have to be borne by the platform.

Another undesirable situation is when the vessel moves while pipe is in the hole. This can result in the pipe being severely bent or actually popping the connection with total loss of the drill string beneath where the pipe connection parted. Typically damage can occur at the **moonpool**/hull interface or near the seafloor if the bottom is extremely hard.

Mining style rigs are much more practical in a **cantilever** mode than are their heavier counterparts. The smaller size also adds to the versatility of rig placement and allows a greater selection of vessels to be used. This over-the-side operation allows larger seafloor frames to be used because they do not have to pass through a **moonpool**. Newer style rigs that are built around a shipping container configuration are much more adept at this type of operation since large support beams are designed into its sub-base so that a separate work platform is not required. Though not the preferred method, many successful coring operations have been completed using a **cantilevered** rig.

4.3 Geotechnical Approaches of Previous Submerged Coral Drilling

4.3.1 Drilling Submerged Coral Reefs: The Lamont-Doherty Experience

The experiences of the group at Lamont-Doherty show that coring of submerged coral reefs can be done successfully from a surface ship, with high recovery rates of pristine coral samples. On two cruises we have cored over 1400 feet of coral, encompassing most of the last deglacial cycle but including coral from the last glacial maximum and some older samples, from the Atlantic and Pacific Oceans. Both cruises used diamond-bit wireline coring rigs from vessels anchored by four-point moorings, in water depths up to 267 feet.

The first coring cruise took place in 1988 off the south shore of Barbados. The vessel used was the R/V Ranger, operated by the US Navy, with a drill rig and crew contracted from Fugro-McClelland. Sixteen individual holes were cored, recovering a total of 1200 feet of core (Figure 17). Coring occurred in water depths of 33 to 267 feet. Targets were three well-developed submarine terraces. The reef crest coral *Acropora palmata* was the dominant species recovered. Lesser quantities of *Montastrea annularis*, *Diploria strigosa*, and *Acropora cervicornis* were also recovered.

The second expedition cored off Kiritimati, Republic of Kiribati, in 1997. Drilling took place from the R/V Moana Wave, a UNOLS ship operated by the University of Hawaii, using a Lamont-owned Acker rig and two drillers from Fugro-McClelland. Eight holes were cored, recovering 220 feet of core. Water depths were 100 to 260 feet. Submarine terraces offshore Kiribati are less extensive and distinct than off Barbados; most of the island is marked by very steep offshore bathymetry. Nonetheless eight holes were successfully cored, recovering over 220 feet of coral. The dominant species in the recovered cores was *Acropora hyacinthus*, a common coral type on the modern fringing reef. Lesser amounts of *Acropora sp*. and *Porites sp*. were also in the cores.

Drilling operations were generally similar on both cruises. Extensive surveys (echosounder, 2.5 kHz, sidescan sonar) were used to locate coring targets. The ship was anchored in its four-point mooring with the bow pointing into the prevailing swell to minimize roll, and thus heave on the drill string. A riser of modified API pipe was set into the bottom, typically in a sandy patch. The riser was weight compensated, and coring proceeded using NQ wireline pipe, with standard core barrel and core catcher. Water and subbottom depths are limited by available riser and drill string.

Our experience proves that there are no major technical barriers to productive coring of submerged coral reef sequences. A number of points have emerged that contribute to successful coring operations:

(1) Complete bathymetric surveys are essential in order to select the best targets. This becomes even more critical in areas of steep bathymetry (i.e., most Pacific atolls) or complex terrace structure.

(2) Deployment of the four-point moorings with sufficient scope allows multiple cores to be taken without resetting the anchors.
(3) Heave compensation is required on the drill string. A minimum of twelve feet of heave compensation is necessary, even in relatively calm seas. Deployment of the rig over the side of the ship (as opposed to a centerwell/moonpool) requires greater heave compensation.
(4) Experienced drillers and crew are required for safe operations and successful coring. As in most wireline operations, constant weight on bit is needed for good core recovery.
(5) Flexible scheduling and multiple targets increase the success rate.
(6) Drilling mud is some times needed in coral reef formations.
(7) Sands are necessary for spudding in the riser and for successful anchoring.
(8) Logging cores as they are raised is critical for sample quality control. If logistics allow, returning selected samples for rapid radiometric age determinations can aid in target selection.

4.3.2 The French Reef Drilling Program

A better understanding of the growth history of Holocene coral reefs including reef growth rates and the distribution of biofacies has been gained via a suite of drilling campaigns that have been carried out by several French institutions (Centre National de la Recherche Scientifique-CNRS, Institut de Recherche pour le Développement - IRD, Commissariat à l'Energie Atomique - CEA) on volcanic islands and atolls (Réunion Island, Mauritius, and Mayotte: Camoin et al., 1997; Tahiti: Bard et al., 1996; Montaggioni et al., 1997; Camoin et al., 1999; Cabioch et al., 1999; Mururoa: Ebren, 1996; Buigues et al., 1997; Camoin et al., 2001), continental margins (New Caledonia: Coudray, 1976; Cabioch et al., 1995), microcontinents (Madagascar ; Seychelles: Braithwaite et al., 2000) and subduction zones (e.g. Vanuatu: Cabioch et al., 1998). These campaigns have been greatly facilitated by the development of drilling capabilities and radiometric-dating techniques over the last 20 years. A brief summary of the drilling approaches used in some of the aforementioned localities and the related results are given thereafter.

Tahiti — The barrier reef-edge at Tahiti has been cored at several locations (Fig. XX) using a Sedidrill 500 drilling machine and coring system. Cores with diameters ranging from 48 to 64 mm were recovered from one vertical (P7) and three inclined (P8, P9 and P10; from 30° to 33° by reference to the vertical) drill holes. Drill holes reached depths ranging from 50 meters below reef surface (mbrs) at P6 to 120 mbrs at P7. Cores P6, P7 and P8 are located on the outer barrier reef flat and are aligned along a 2500 m-long transect on the barrier reef. Drill holes P9 and P10 are located at the edge of the Papeete pass, which corresponds to the entrance of the harbor (Figure 18).

Core recovery in the P-series cores was dependent upon framework type and on the size of internal cavities, but ranged from 50 to 95%; sections with poor or no recovery generally correspond to unconsolidated sands. During drilling, the tube barrel was advanced in 1.5-m increments; core depths were estimated with ± 0.3-m accuracy.

Mururoa — Drilling operations have been carried out by CEA in the lagoon (vertical cores of several hundreds of meters) and throughout the outer reef flank of the atoll (300 m-long ocean-deviated drill-holes with inclination of 30°, 40° and 45° with respect to the horizontal).

Volcanic islands of the Indian Ocean — One vertical borehole was drilled throughout the fringing reef of La Saline (FRE drill hole; Réunion Island), about 150 m behind the reef front where communities of branching corals prevail. Three cores were recovered from the Pointe-aux-Sables fringing reef (PS drill holes; Mauritius), respectively in the central part of the reef flat (PS-2), in the inner part of the reef flat (PS-1) and in the back reef zone (PS-3). Ten boreholes were drilled throughout the barrier reef south of Pamandzi islet (Mayotte; PMI-1 to PMI-10 drill holes). The length of the cores varied between 16 m and 30 m and the recovery, ranging between 20 and 80%, depended on the nature of material encountered. Very poor to no recovery occurred in sections containing fine sands, as evidenced by sandy grains retained in the core catcher. Core recovery was higher in the outermost parts of reef flats and barriers, due to higher volume of reef framework material and the greater degree of lithification of this material.

Seychelles — In November 1995 seven vertical holes were drilled obliquely across the northern edge of the reef at Anse aux Pins. A tractor-mounted, rotary-drilling rig of the Gondwana Drilling Company was used for the drilling. The large wheels and load-spreading characteristics of this vehicle allowed us to position it directly on the reef margin on what surface observations suggested was coral-algal frame, selecting a period of low tides and relatively calm weather. The strategy employed was to drill during periods of low water and to retreat as the tide rose. A diamond drill bit and a double-walled core barrel 76mm in diameter were key elements in a wire-line system that allowed us to withdraw core through the large diameter drill rods, thus eliminating the general need for casing and the risks of hole collapse. We nevertheless cased the uppermost 1.5m of holes to improve surface stability. Core recovery of coral-rich sections was good but sections containing loose sands, which proved to be volumetrically important, commonly gave poor or no recovery.

4.4 Geotechnical Requirements for Submerged Coral Drilling

Coral scientists need to provide the geotechnical community with sufficient information (Table 4.6) before an estimate of costs can be calculated. Some of the required information includes:

1. Location, including distance from port facilities, water depth, weather window(s).
2. Drilling target, including number of holes (duplicate?), core depths, expected lithologies.
3. Other support costs, principally crew boat cost.
4. Environmental. Can we anchor? Is DP required or desirable?
5. Expected sea state (swell height and frequency).
6. Tidal range.
7. Currents; direction and velocity.
8. Local excise, duties and taxes - both corporate and personal.
9. In country transport and accommodation.
10. Address any governmental and/or cultural issues associated with drilling and removing coral samples.

5 The Future of Submerged Coral Drilling

Previous submerged coral drilling campaigns have been scientific and technical triumphs (e.g., Barbados, Tahiti and Christmas Island). These previous programs were accomplished not through a global ocean-drilling program such as ODP, but rather through the heroic efforts of a small group or even individual investigators. Despite such efforts the spatial and temporal coverage of Late Quaternary climate and sealevel studies using submerged corals remains limited and the rate at which new coral drilling campaigns are initiated has been slow. The submerged coral drilling community is at a crossroads. We can continue the approaches of the past by which individual or small groups of investigators make incremental progress on solving compelling scientific questions or we can attempt to develop a coordinated, international, submerged coral drilling program. The initiation of an independent, international, submerged coral drilling program presents some daunting logistical challenges in terms of program structure funding, proposal writing, project management, core handling and storage, analytical protocol, etc. Alternatively, the submerged coal drilling community could choose to take advantage of the greater than 30 years of experience in DSDP/ODP and become active participants in the new drilling program, IODP. Participation in IODP by the submerged coral drilling community requires that IODP fully embrace a fit-to-mission philosophy by actions, not just words. The Conference on Multiple Platform Exploration (COMPLEX) Report is especially strong in the traditional areas of ODP science activities related to deep-ocean sediment and oceanic lithosphere drilling, but provides little emphasis on shallow-water science, especially that related to coral studies. SCDW participants view the COMPLEX Report as a lost opportunity, but are excited that the European Standing Committee on Ocean Drilling (ESCOD) and the European Science Foundation (ESF) organized a meeting in Brussels in January, 2001 the theme of which was Alternate Platforms as the Third Leg of IODP. A Joint European Oceanic Drilling Initiative (JEODI) was presented at the Brussels meeting and an Alternative Platform Drilling Conference (APLACON) is scheduled for May, 2001 in Lisbon, Spain. Participants of the SCDW strongly endorse and applaud these European initiatives because neither the riser or non-riser drillship of IODP will be well suited for shallow-water drilling, especially submerged coral drilling.

A cultural change in the ocean sciences needs to occur coincident with the transition from ODP to IODP. The new program needs to be open to those communities that have historically felt disenfranchised by ODP, largely because of the limitations of the Joides Resolution. The challenge in front of IODP is to be flexible enough to drill the scientific proposals that are highest ranked, regardless of the platform that is required to accomplish the highest priority scientific objectives, as long as they are reasonable from an economic perspective. One approach to meeting this challenge is the creation of a "geotechnical" committee consisting of scientists and engineers that would determine the most appropriate platform to drill highly ranked scientific proposals. In such a system, PIs whose drilling objectives require alternate platforms would concentrate their efforts on the science in the proposal. The "geotechnical" committee would work with the PIs of the highly ranked scientific proposal to determine all the drilling parameters and variables need to form a "request for drilling bids". The global geotechnical drilling community could then provide a series of bids for the successful completion of the scientific objectives specific to a specific bid. The "geotechnical committee" would evaluate all of the bids and recommend the best drilling solution — riser, non-riser or alternate platform (e.g., geotechnical vessel, barge, seabed frame). Such a system would provide immediate benefit to siliciclastic and carbonate margin communities, as well as to the submerged coral drilling community. Perhaps just as important, such a system would permit the two drillships of IODP to concentrate their efforts where they are best suited (e.g., deep water/deep penetration/piston coring), while leaving shallow-water drilling to platforms specifically designed for drilling and recovering of materials in these waters.

Figures

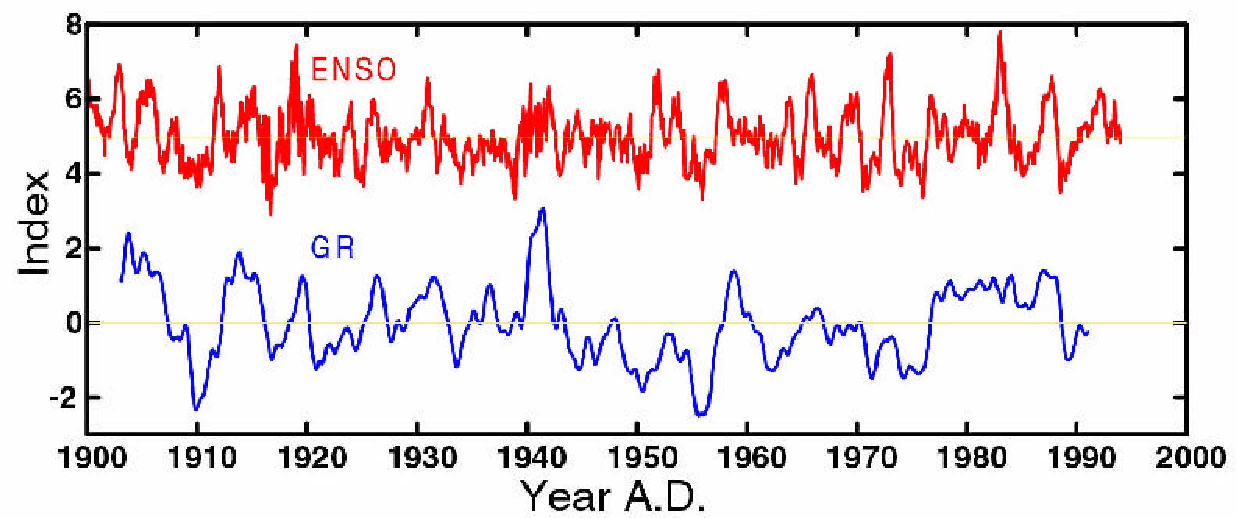

Figure 1. Time series of ENSO (upper line in red) and the decadal ENSO-like (GR - lower line in blue) climate variability. The index of ENSO is the cold tongue index (CT), which is the SST averaged monthly and from 4°N to 4°S, 90°W to 180°W. The index of the decadal ENSO-like variability is the time series of the dominant pattern of global SST anomalies after the ENSO-related (CT) SST anomalies have been removed from the global SST data (from D. Battisti using data in Zhang et al. 1997).

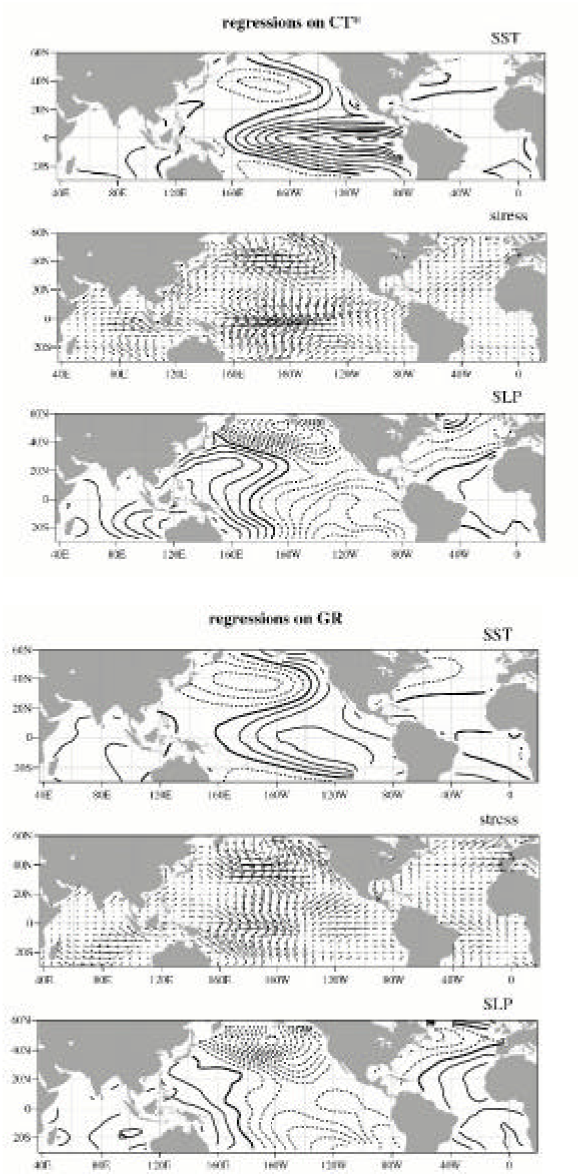

Figure 2. Global fields regressed upon the monthly ENSO (CT) time series and the monthly ENSO-like decadal variability (GR) time series, as displayed in Figure 1. Top panel: Sea Surface Temperature, Middle: wind stress, and Bottom: Sea Level Pressure. The contour interval is (per unit standard deviation): (top) 0.1°K, (middle) 8.3 m2 s-1 for the longest vector, and (bottom) 0.1 Mb. Negative contours are dashed and the zero contour is thickened. Reproduced from Figures 11 and 12 of Zhang et al. (1997).

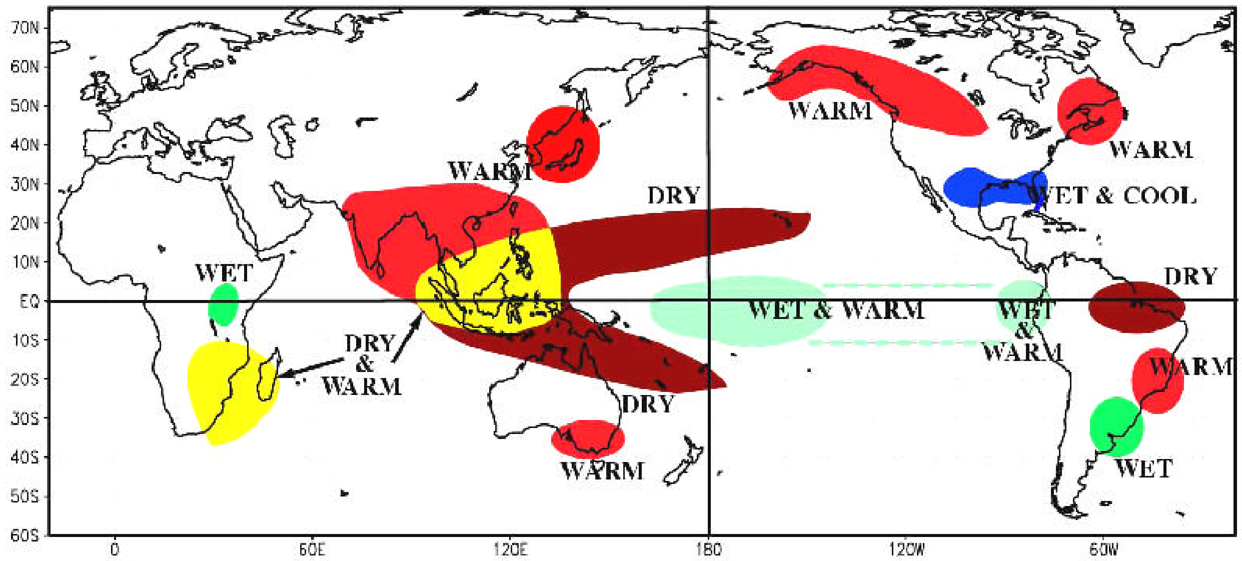

Figure 3. Commonly observed ENSO warm mode impacts during December-January (NOAA Network Information Center, at http://www.nnic.noaa.gov/products/analysis_monitoring/ensostuff/).

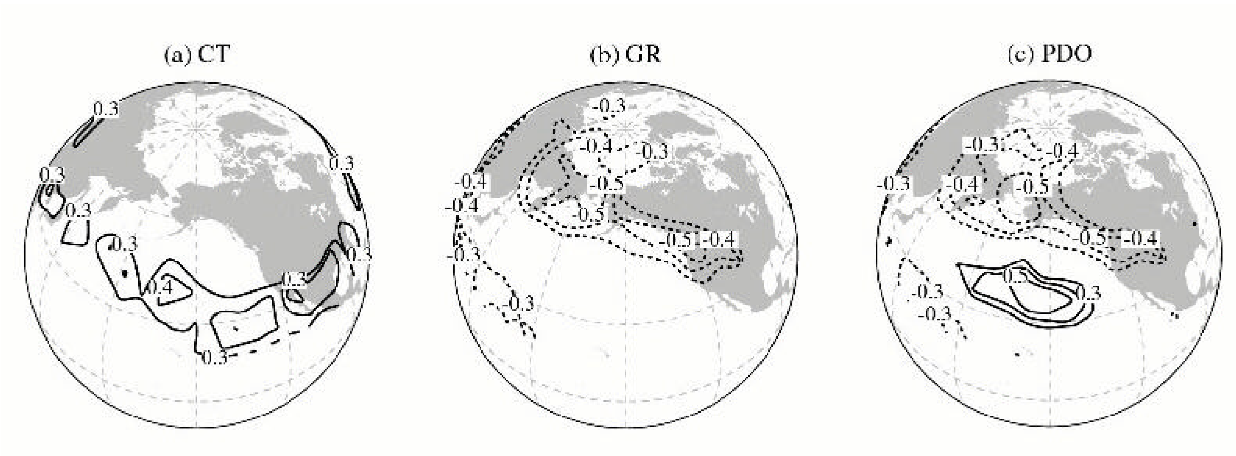

Figure 4. Correlation maps of the winter mean storminess (NDJFMA band-passed 500 mb height anomalies) with winter mean climate indices for the period 1947-1994. Maps show correlations between storminess and indices of a) ENSO (the Cold Tongue index - CT), b) the decadal ENSO-like variability (the Global Regression - GR - minus the CT), and c) the Pacific Decadal Oscillation (PDO) as defined by Mantua et al. (1997). Contours show correlations exceeding the 95% confidence level where each year is considered to be independent of the last. Positive correlations indicate more storminess associated with warmer water in the tropical Pacific and colder water in the North pacific. Reproduced from Figure 11 of Bitz and Battisti (J. Climate, 1999).

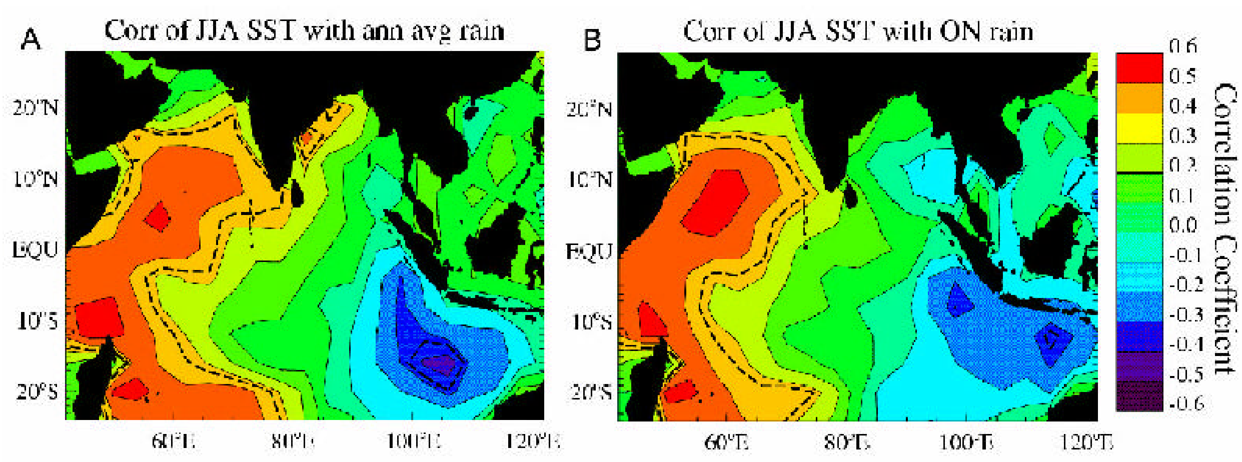

Figure 5. Map of correlation coefficients between June-August Indian Ocean SST anomalies and East African coastal rainfall for A) full year and B) October-November. The correlation pattern indicates that during rainy periods on the East African coast, offshore SST is warm and eastern Indian Ocean SST is cool, with implications for zonal atmospheric circulation over the tropical Indian Ocean. SST data are from the Global Sea Ice and Sea Surface Temperature (GISST) data set (Parker et al. 1995) and the coastal rainfall data represent 7 coastal sites in Kenya and Tanzania from the Global Historical Climatology network (available at http://cdiac.esd.ornl.gov/cdiac). Analysis spans the period 1950-1990. From Cole, Clark, and Webster (2000).

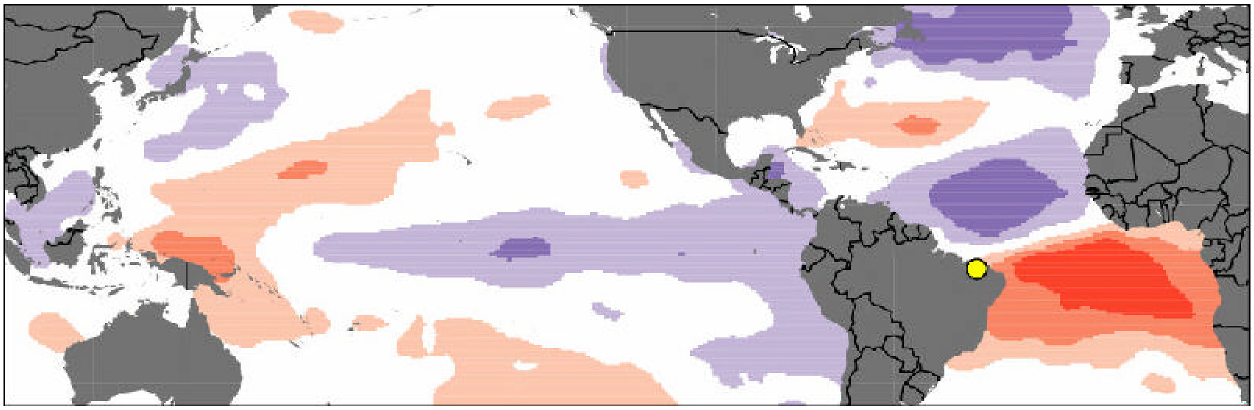

Figure 6. Correlation between average Feb-May precipitation in northeast Brazil and sea surface temperature. Red (blue) shading indicates regions in which above normal SSTs tend to be observed in conjunction with above (below) normal rainfall in Northeast Brazil. The strongest correlations are on the order of 0.7. Northeast Brazil rainfall tends to be more strongly correlated with Atlantic sea surface temperatures than with Pacific sea-surface temperatures. The precipitation time series is the average of 6 stations from northeastern Brazil (including Fortaleza and Quixiramobim) and the SST is from COADS. The analysis period is 1946-1985. From "Pan American Climate Studies: Prospectus and Implementation Plan", available at http://www.atmos.washington.edu/gcg/PACS2/newPACS/pacs.new.pdf.

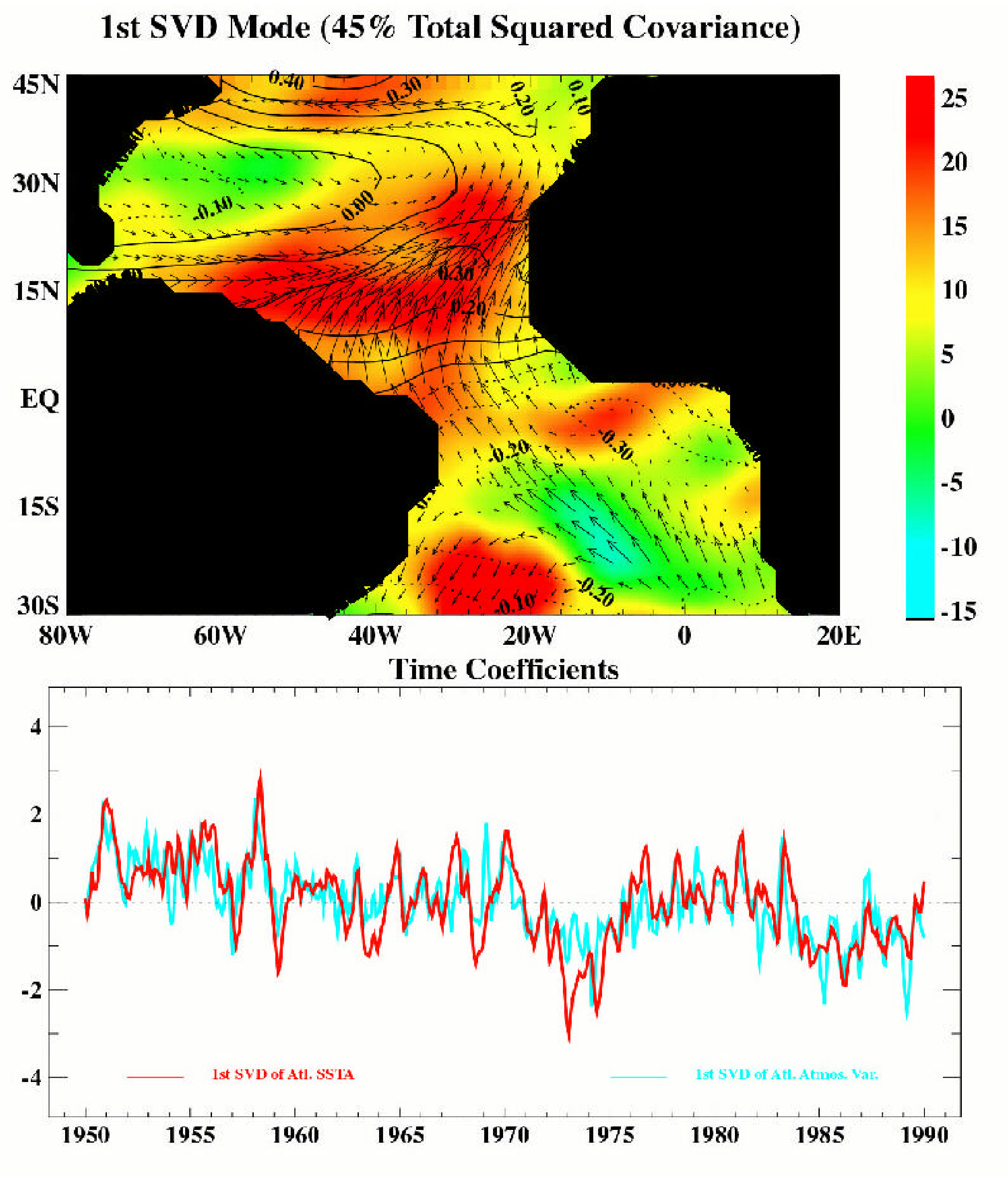

Figure 7. The Atlantic dipole-like variability as illustrated by a joint singular value decomposition (SVD) analysis of monthly mean ocean surface data from 1950-1989 A.D. The data source is the reprocessed Comprehensive Ocean-Atmosphere Data Set (COADS). The upper panel shows the spatial structure of the first SVD mode. Contours show SST anomaly in °C. Vectors depict wind stress anomalies. Colors indicate the strength of surface heat flux anomalies in W m-2. The first SVD mode explains about 45% of the total squared variance in this coupled system and has a dipole-like SST pattern with maximum amplitudes at about 15°S and 15°N. The lower panel shows two associated time series (in red, the first SVD of Atlantic SST anomalies; in blue, the first SVD of Atlantic atmospheric variation. The time coefficients have been normalized by their own standard deviations. From Figures 1a and 1b of Chang et al. (1997). Reprinted with permission of Nature.

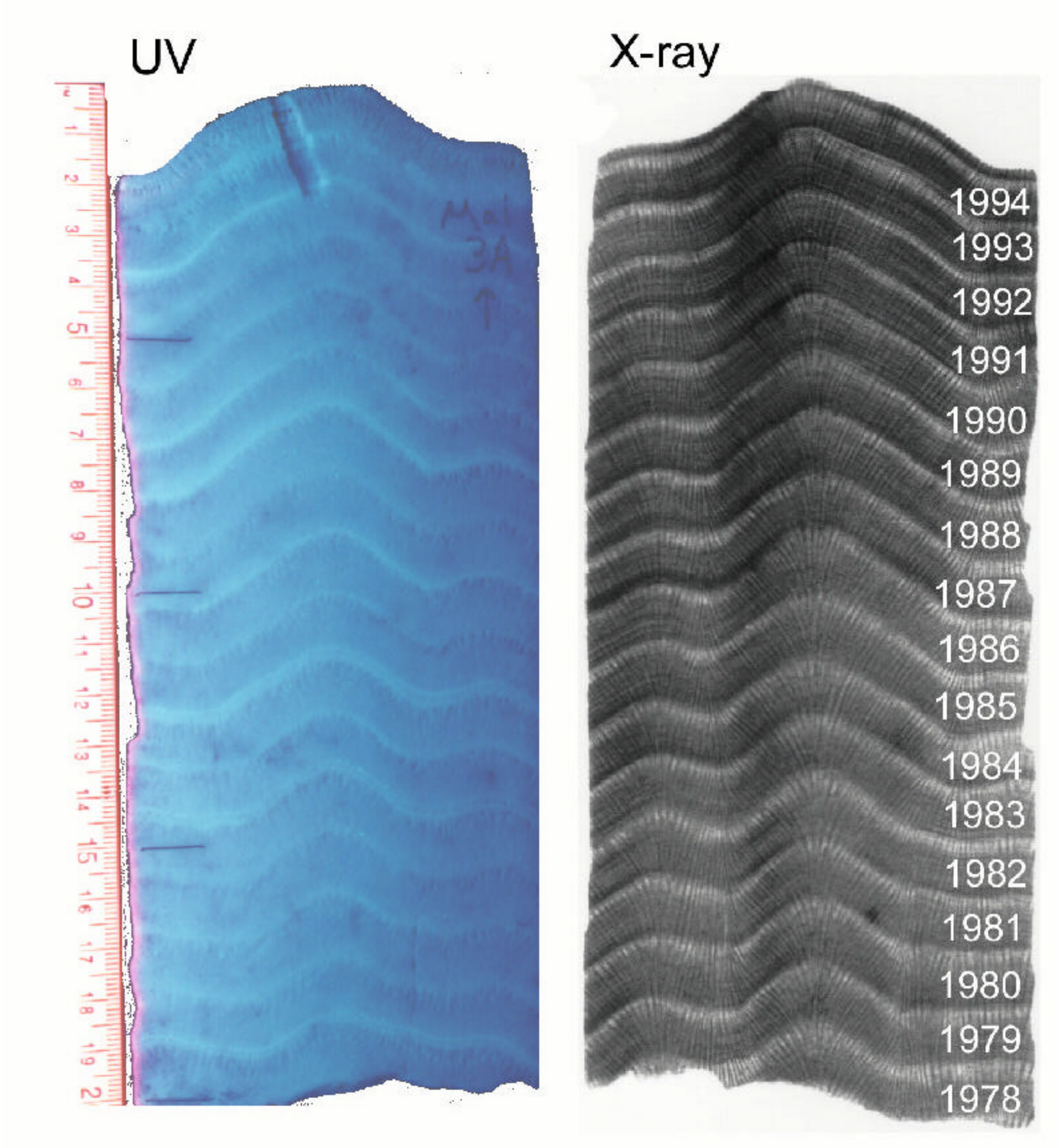

Figure 8. X-radiograph (right) and photograph of a coral slab illuminated under ultraviolet light (left). White numbers indicate assigned year of growth. The coral core was collected from a 4-meter high specimen of Porites lutea from Malindi Marine Park, Kenya. This photograph shows the upper 20 cm (1994 to 1978 A.D.) of a chronology that extends back to 1692 A.D. Centimeter ruler is at left. The X-radiograph reveals annual variations in coral skeletal density that result from small changes in the relative magnitude of extension rate versus calcification rate. The bright bands that result from visual wavelength fluorescence under excitation with ultraviolet light most likely result from terrestrial organic substances that are incorporated into the coral skeleton during the annual monsoons. Both X-ray and UV bands can be correlated between cores from a single head and between cores from within a site and thus comprise useful chronologic and cross-dating tools. From Dunbar and Cole (1999).

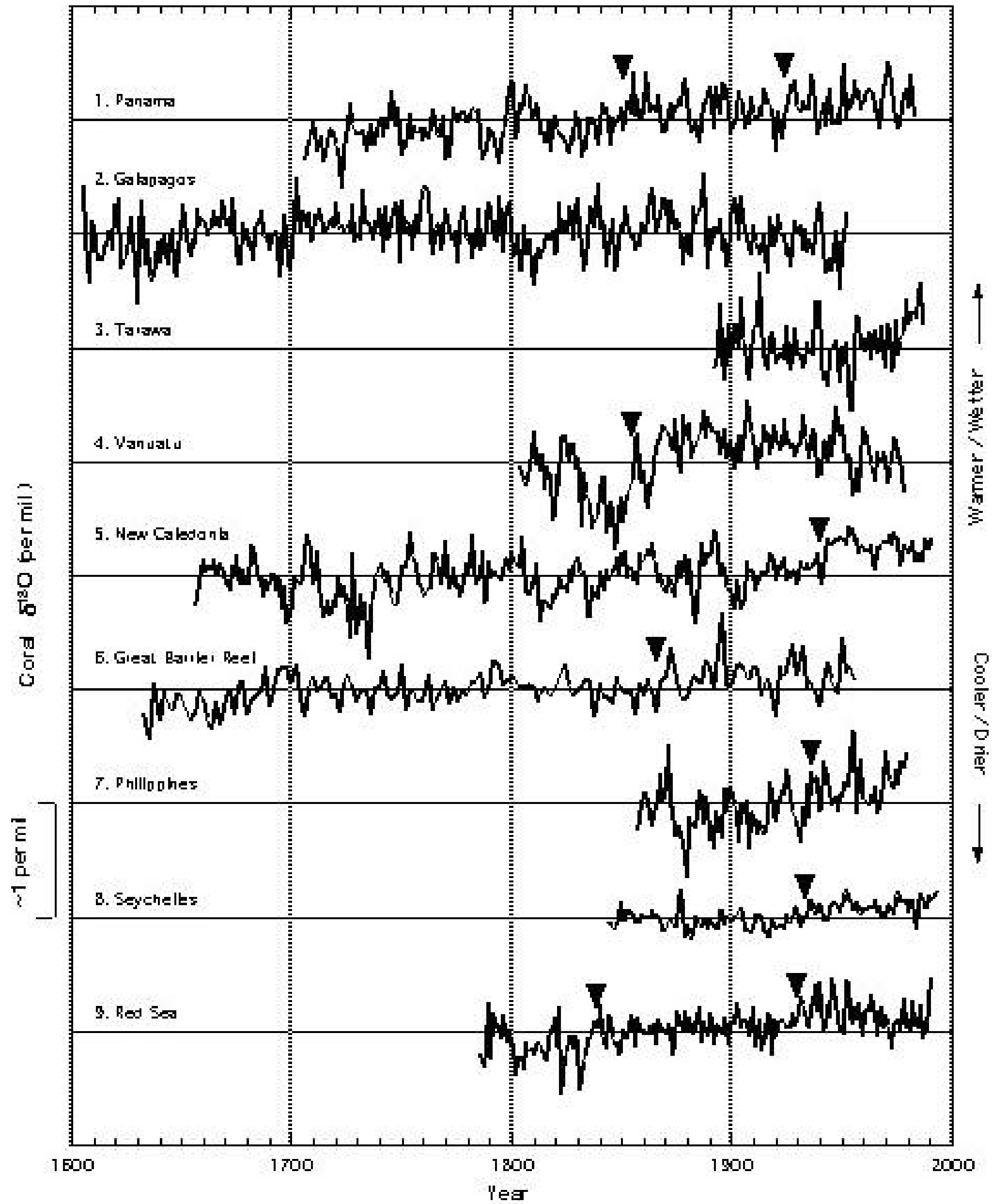

Figure 9. Comparison of annual mean coral $\delta^{18}O$ records in the Pacific and Indian Ocean region extending back more than 100 years. Horizontal lines show the mean $\delta^{18}O$ value for each site. Black triangles mark approximate times of abrupt shifts in $\delta^{18}O$ heralding warmer/wetter conditions. Data are from the World Data Center-A for Paleoclimatology, NOAA/NGDC Paleoclimatology Program, Boulder, Colorado, USA (http://www.ngdc.noaa.gov/paleo/coral) and the original references. Details of cores (locality, species name, time-span of record, original reference) are as follows: 1. Gulf of Chiriqui, Panama (83S, 823W; Porites lobata; 1708-1984; Linsley et al., 1994); 2. Urvina Bay, Galapagos, Ecuador (03S, 913W; Pavona clavus and P. gigantea; 1607-1981; Dunbar et al., 1994); 3. Tarawa Atoll, Republic of Kiribati (13N, 1723E; Porites spp.; 1893-1989; Cole et al., 1993); 4. Espiritu Santo, Vanuatu (153S, 1673E; Platygyra lamellina; 1806-1979; Quinn et al., 1993); 5. Amedee Lighthouse, New Caledonia (223S, 1663E; Porites lutea; 1657-1992; Quinn et al., 1998); 6. Abraham Reef, Great Barrier Reef, Australia (223S, 1533E; Porites australiensis; 1635-1957; Druffel and Griffin, 1993); 7. Cebu, Philippines (103N, 1243E; Porites lobata; 1859-1980; Patzold, 1986); 8. Mahe Island, Seychelles (53S, 553E; Porites lutea; 1846-1995; Charles et al., 1997); 9. Aqaba, Red Sea (293N, 353E; Porites sp.; 1788-1992; Heiss, 1994; data for vertical core). From Gagan et al. (2000).

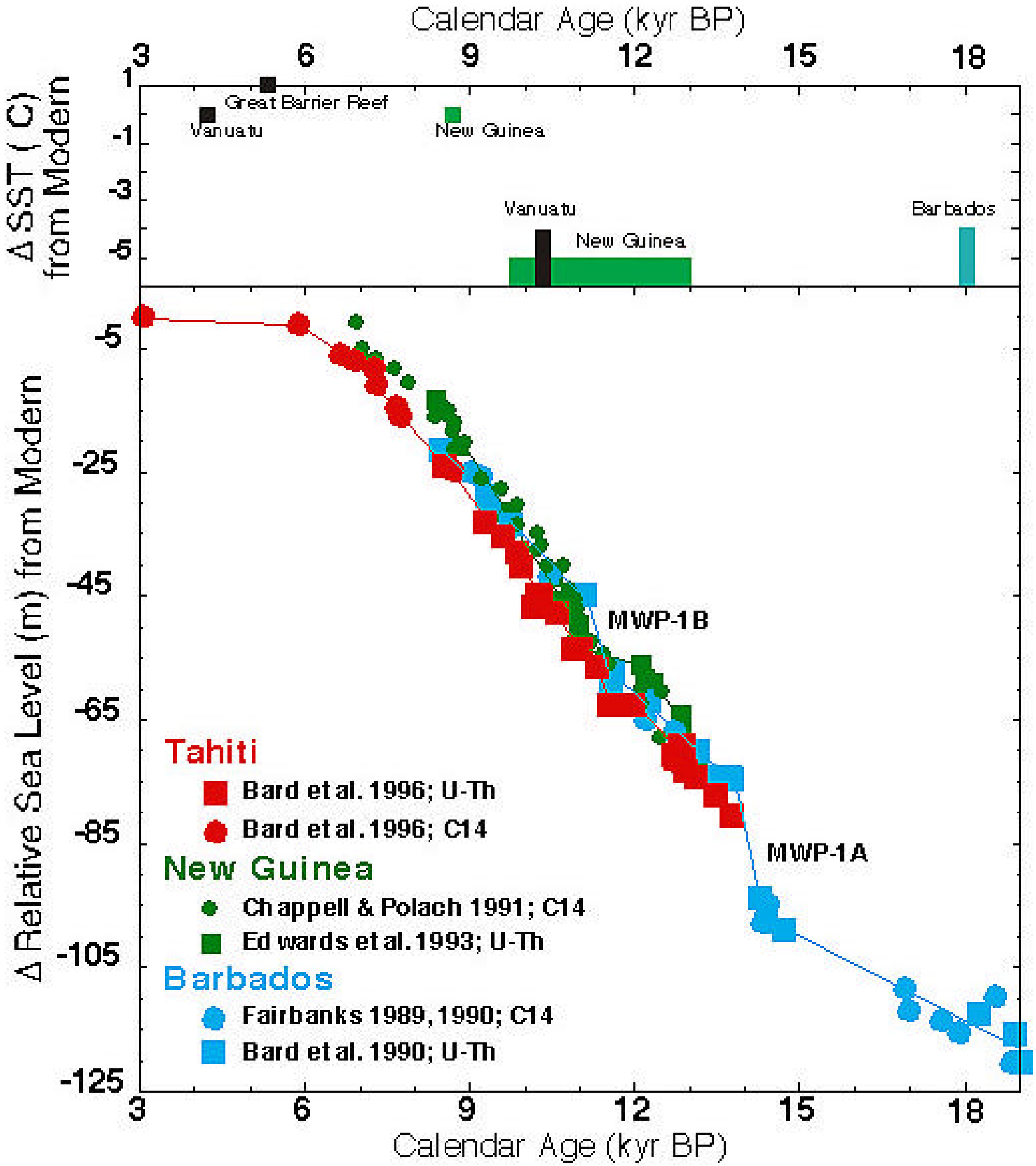

Figure 10. Deglacial climate and sealevel reconstructions based on corals. The top panel is a summary of tropical SST estimates based on the geochemistry of coral skeletons (Guilderson et al., 1994; Min et al., 1995; Beck et al., 1997; Gagan et al., 1998). The lower panel is a summary diagram of deglacial sea level curves from Barbados, New Guinea, and Tahiti (Bard et al., 1996). From Quinn and Mountain (2000).

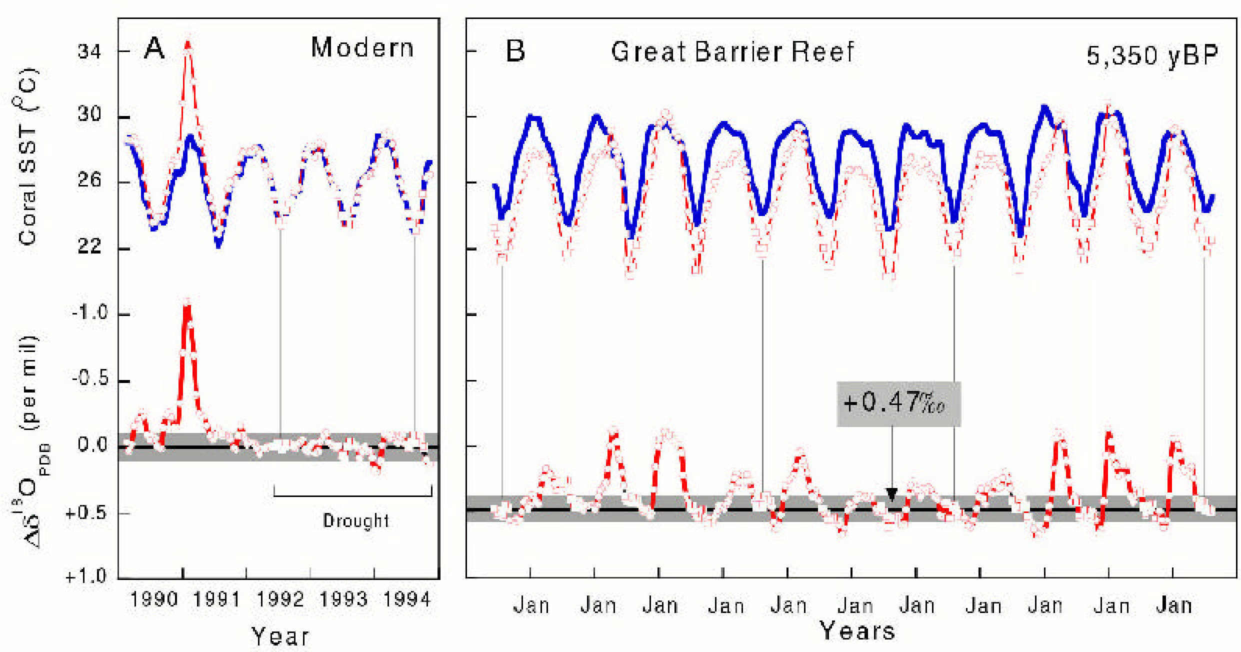

Figure 11. Comparison between sea surface temperatures calculated from coral Sr/Ca ratio (blue curves) and $\delta^{18}O$ (upper red curve) for modern (left) and 5,350 yrs BP (right) Porites corals from Orpheus Island, central Great Barrier Reef, Australia. Differences in seawater $\delta^{18}O$ (lower red curves), relative to the modern mean, are obtained by removal of the temperature component of the $\delta^{18}O$ signal ($\Delta\delta^{18}O$). The horizontal lines show the mean $\Delta\delta^{18}O$ of seawater, as defined by the seven $\Delta\delta^{18}O$ values (squares) falling in the austral winters (vertical lines). Relative to the mid-Holocene, the modern coral indicates cooler average water temperatures (by 1.2°C and the characteristic interannual variability in salinity (~$\delta^{18}O$seawater) that accompanies the ENSO cycle (from Gagan et al. 1998).

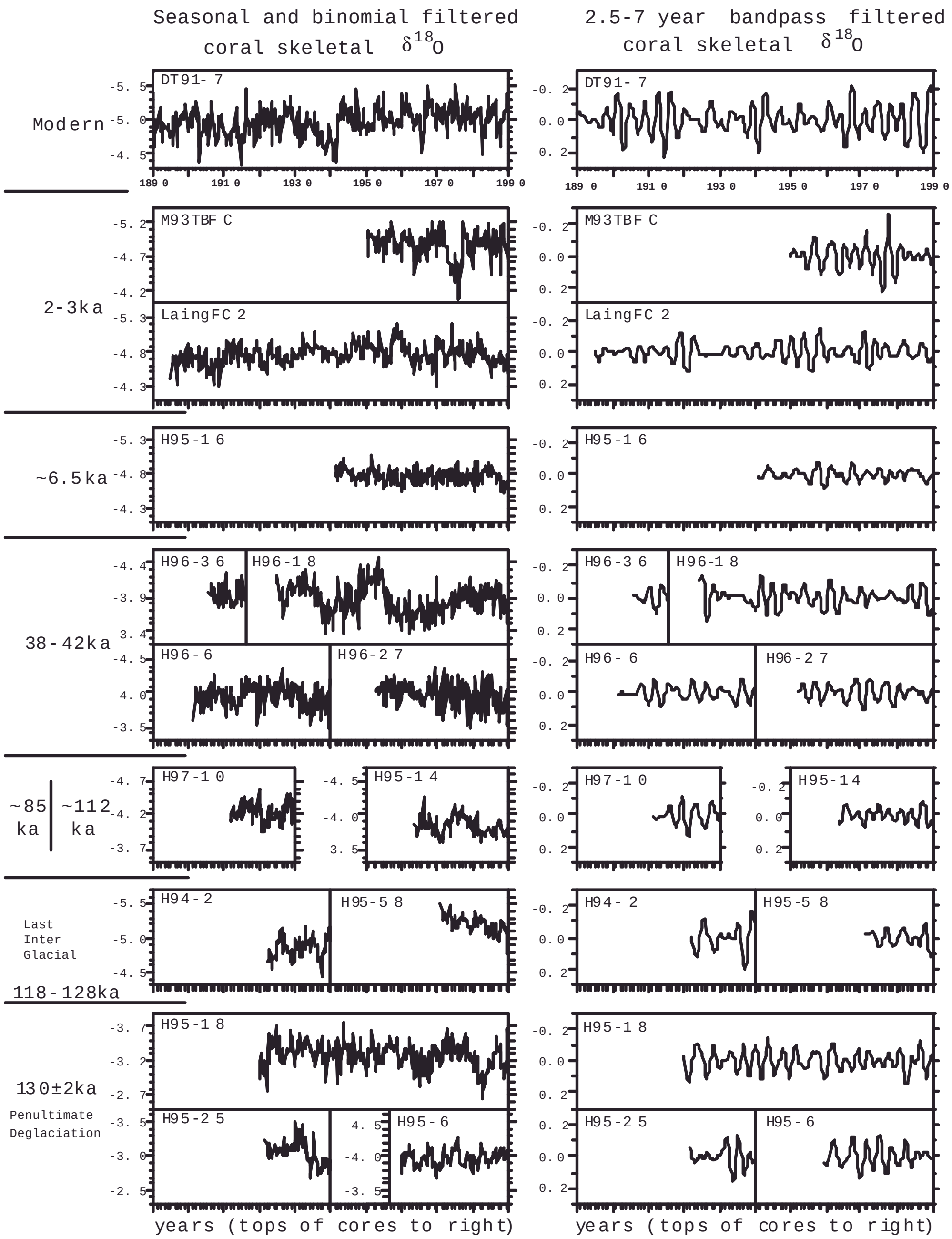

Figure 12. Paleo-ENSO variability from fossil corals. Left hand side: Seasonal resolution (thin lines) and 2.25 year binomial filtered (thick lines) skeletal $\delta^{18}O$ records from all fossil corals used in this study, with the record from modern coral DT91-7 shown for comparison. Right hand side: 2.5-7 year (ENSO) bandpass filtered coral $\delta^{18}O$ time series. Right-hand side. Standard deviation of the 2.5-7 year (ENSO) bandpass filtered time series of all modern and fossil corals discussed in this study. An asterisk after the coral label indicates that the time series is < 30 years long. The horizontal dashed lines indicate maximum and minimum values of standard deviation for 30-year increments in the modern coral records. From Tudhope et al. (2001).

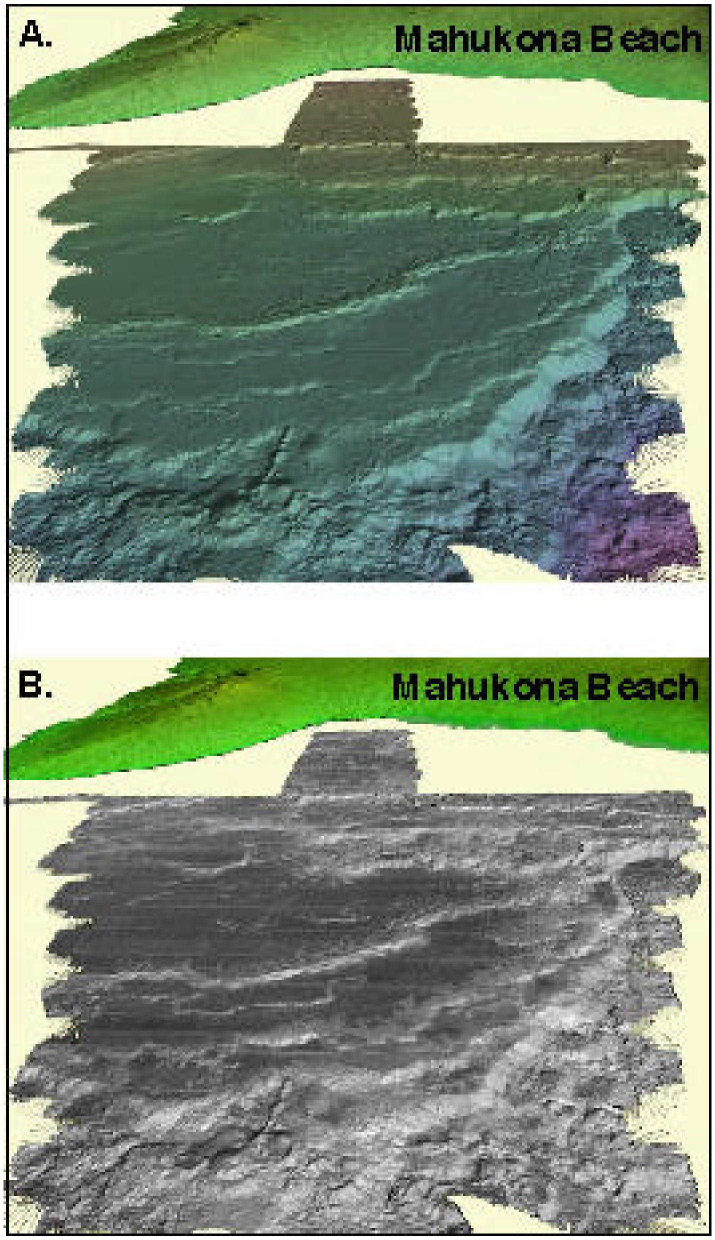

Figure 13. (A.) Colored bathymetric 3-D view of the reefs off Mahukona Beach, Hawaii with no vertical exaggeration. The view is from the west-northwest looking towards the island of Hawaii, which is shown in the background. The data were gridded at 20 m to create the image. (B.) Same view as in (A.), but showing the sidescan data draped on the bathymetry. The sidescan is displayed so that high acoustic backscatter is bright and low is dark. The coral reefs and some lava flows have high acoustic backscatter and are bright in the image whereas the sediment-covered lagoons behind the reefs have low acoustic backscatter. From David Clague, unpublished data.

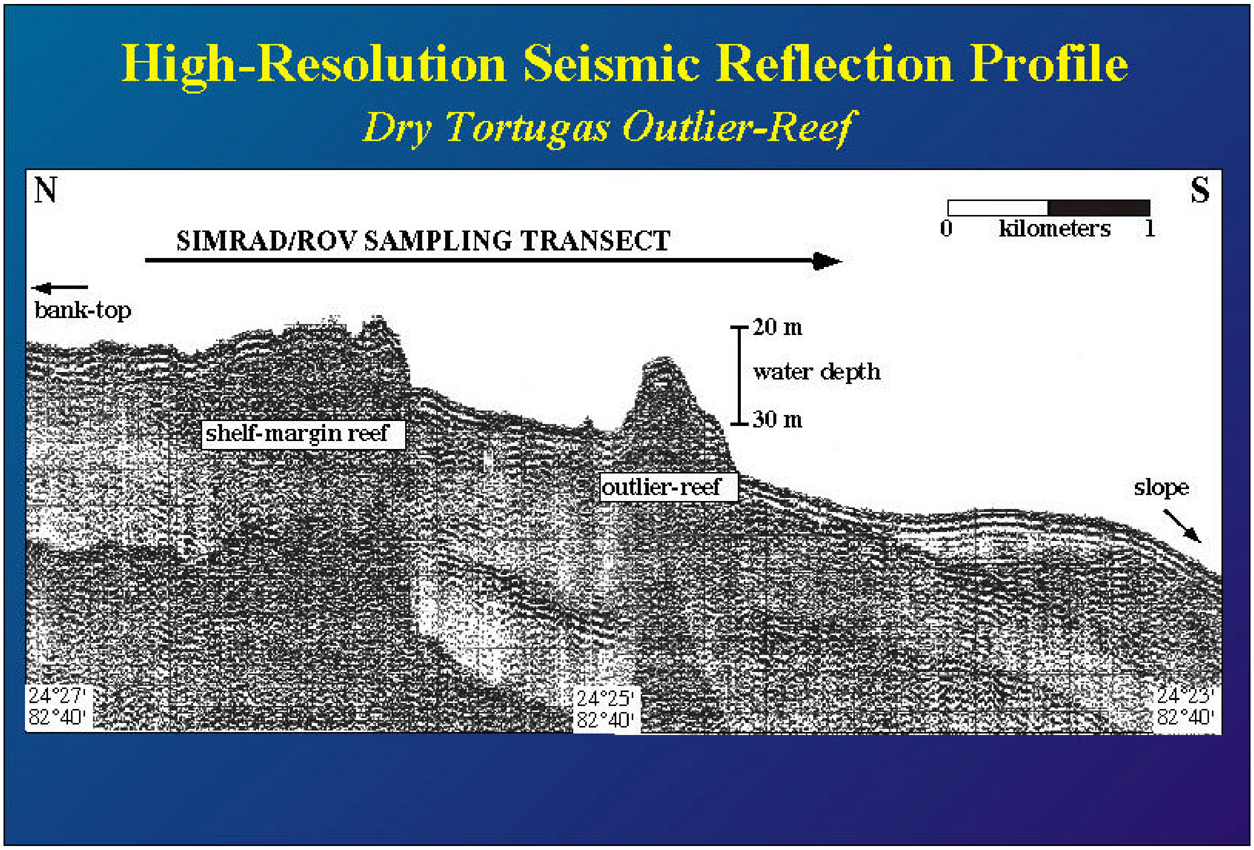

Figure 14. Seismic reflection profile line across the Dry Tortugas Outlier Reefs. From Al Hine, unpublished data.

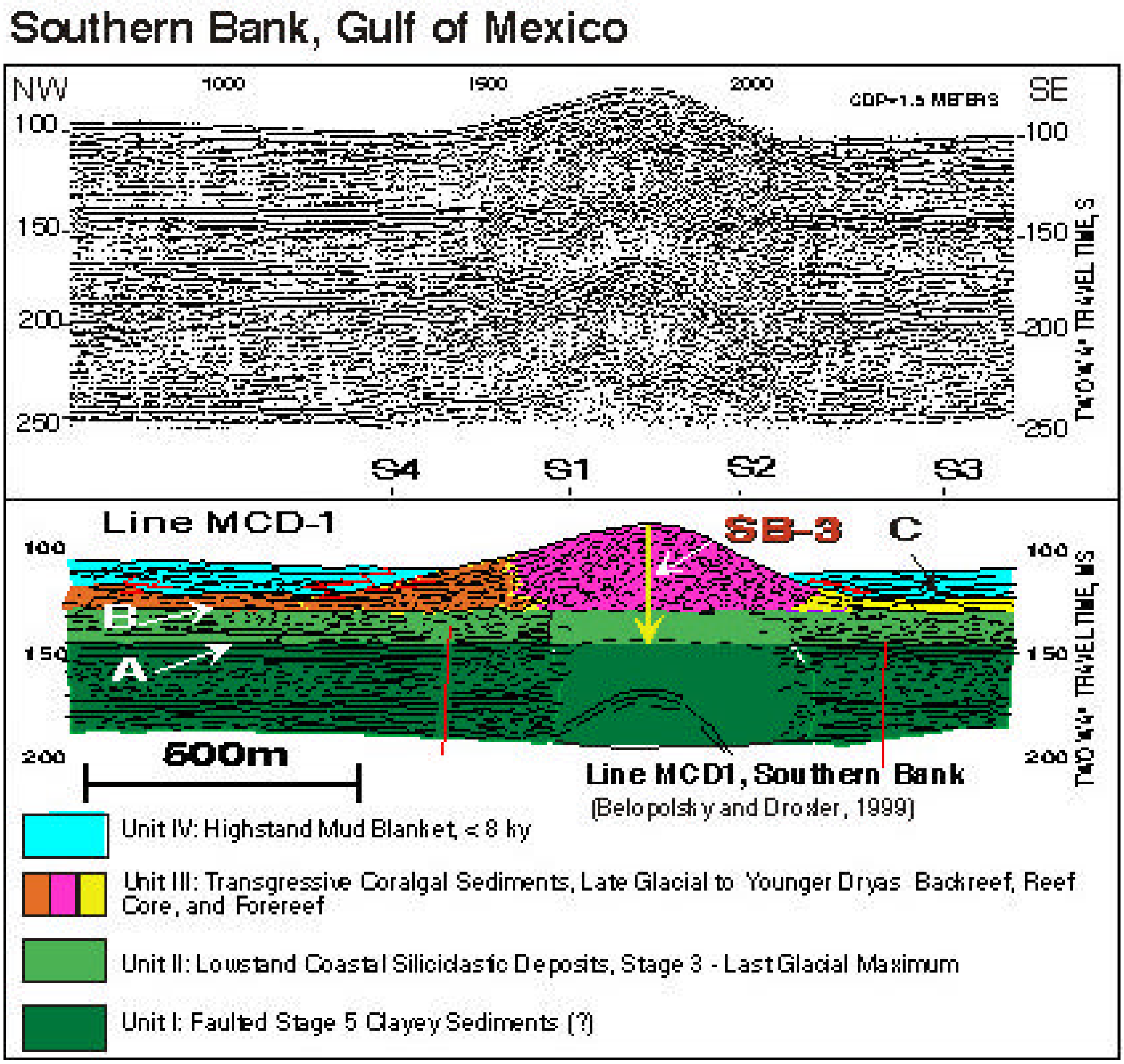

Figure 15. High-resolution, 24 channel seismic line across Southern Bank, Gulf of Mexico. Three sub-seafloor prominent reflectors, referred to from the lower to the upper part of the seismic image as A, B, and C, delineate four distinct seismic units I to IV in the seismic lines. The seismic lines image well the external morphology and partially internal architecture of Southern Bank fossil coralgal reef or Unit III, bounded by reflectors B and C. This Unit III includes also the contemporaneous sediments surrounding the coralgal edifice of Unit III. In addition, the seismic lines display the geometrical relationship between the reefal unit itself (Seismic Unit III) and the sedimentary deposits (Seismic Units I and II) on top of which the reef was established and then flourished, and the youngest sediments (Seismic Unit IV) within which it was finally partially buried. From Andre Droxler, unpublished data.

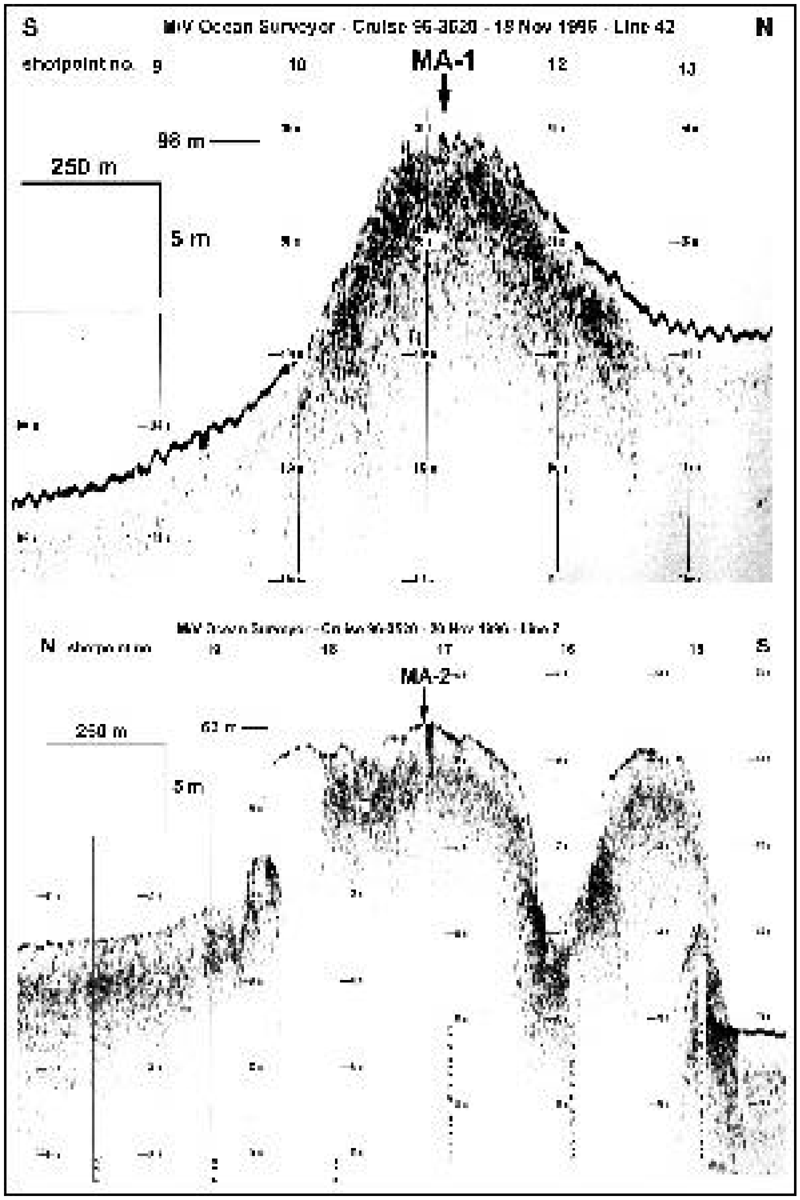

Figure 16. CHIRP sonar profile of carbonate mounds on the Mississippi-Alabama outer continental shelf.

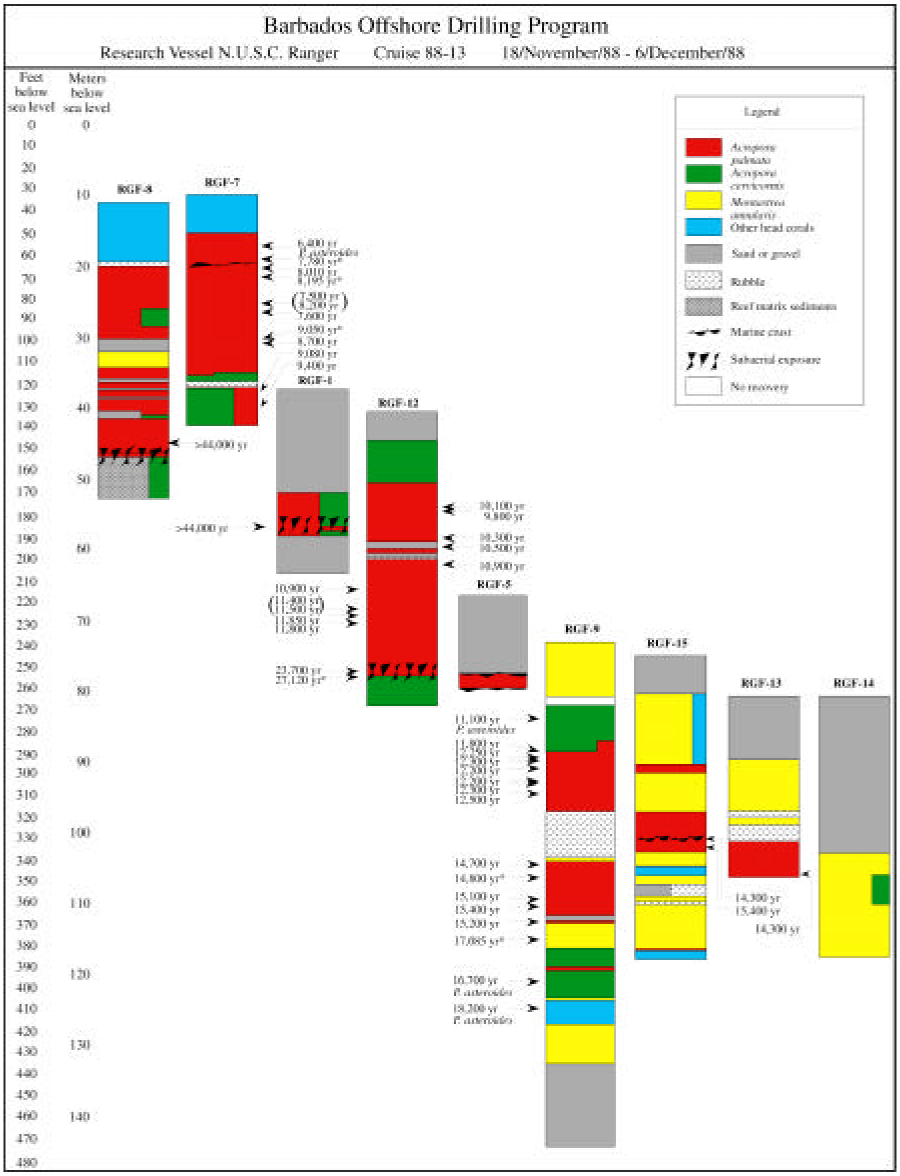

Figure 17. Stratigraphy of coral cores obtained from offshore Barbados (Fairbanks, 1989).

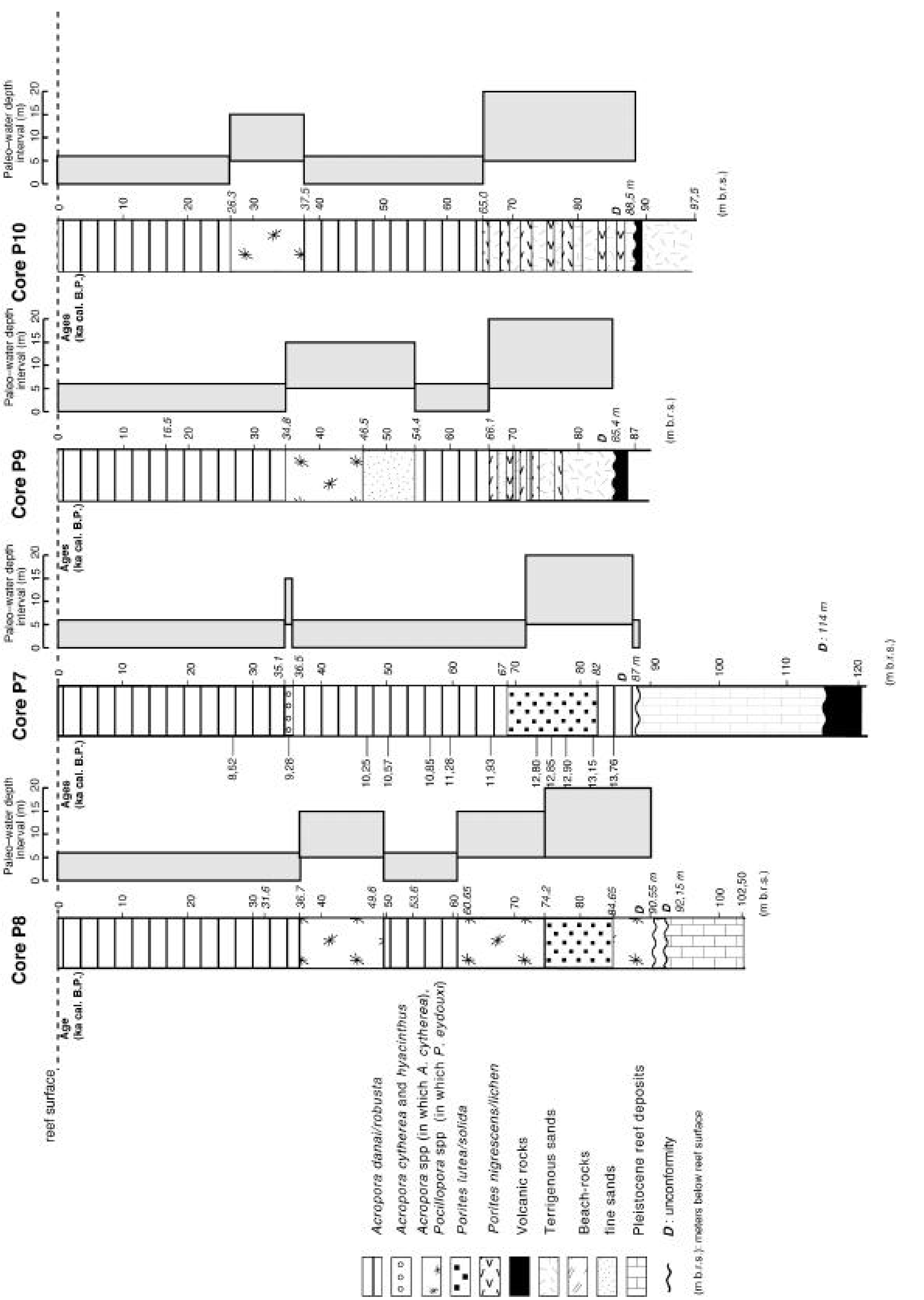

Figure 18. Stratigraphy of coral cores from Tahiti (from Cabioch, Camoin & Montaggioni, 1999).

Tables

Table 4.1 Comparison of Samplers Available for Various Pipe Sizes

Item	Description	Sampling	Steel API Pipe w/ Upset Tool Joints			Al. Pipe	Geobor
		Method	3.5"	4.5"	5"	5"	5.5"
1	**Dimensions of pipe**						
1a	OD tube body, inches	n/a	3.5	4.5	5	5.125	5.5
1b	ID tube body, inches	n/a	2.764	3.826	4.276	4.125	4.94
1c	OD tool joint,inches	n/a	4.75	6.25	6.625	7	5.5
1d	ID tool joint,inches	n/a	2.75	3.5	4.0625	4.0625	4.94
1e	submerged weight/ft(note 2)	n/a	12.5	16.3	21.2	8.3	13.6
1f	nornal bit size, inches	n/a	5.5-6.5	7.5-8.5	8.5-10	8.5-10	6-7
2	**Soil Samplers**						
2a	2 1/4" thin walled shelby tube	push	yes	yes	yes	yes	yes
2b	2" split spoon	percussion	yes	yes	yes	yes	yes
2c	2 1/4" liner sampler	push	yes	yes	yes	yes	yes
2d	2 14" thick wall taper tube	percussion	yes	yes	yes	yes	yes
2e	3" thin wall shelby tube	push	no	yes	yes	yes	yes
2f	3" piston sampler	hydraulic	no	yes	yes	yes	yes
2g	3" thick wall taper tube	percussion	no	yes	yes	yes	yes
2h	3" piston liner sampler	hydraulic	no	yes	yes	yes	yes
2i	2.2" rapid piston sampler	hydraulic	no	yes(4)	yes(4)	yes(4)	yes(4)
2j	2.05" Pilot rotary corer	rotary	no	yes(4)	yes(4)	yes(4)	yes(4)
2k	1.5" split tube sampler	percussion	yes	yes	yes	yes	yes
2l	1.625" swelling soil barrel	push	yes	yes	yes	yes	yes
2m	165 lb wireline percussion hammer	percussion	yes	yes	yes	yes	yes
2n	300 lb wireline percussion hammer	percussion	no	yes	yes	yes	yes
2o	Geobor S shelby tube	push	no	no	no	no	yes
3	**In situ testing/speciality tools**						
3a	umbilical type CPT/PCPT	hydraulic push(1)	no	no	yes(4)	yes(4)	yes(4)
3b	Dolphin Remote vane	push	no	no	yes(4)	yes(4)	yes(4)
3c	Dolphin CPT/PCPT	hydraulic push(1)	no	no	yes(4)	yes(4)	yes(4)
3d	2.2" hydraulic hammer sampler	hydraulic hammer	no	no	yes(4)	yes(4)	yes(4)
4	**Boart Longyear Geo-Barrel**						
4a	2" push	push	no	no	yes	yes	yes
4b	3" push	push	no	no	yes	yes	yes
4c	2.155" pilot corer	rotary/wireline	no	no	yes	yes	yes
4d	2.937" pilot corer	rotary/wireline	no	no	no	no	yes
4e	3.345" hard rock core	rotary/wireline	no	no	no	no	yes
4f	2.5 " hard rock core	rotary/wireline	no	no	yes	yes	yes
5	**Hard Rock Coring Systems**						
5a	BQ - diamond coring	rotary/wireline	yes(3)	yes(3)	yes(3)	yes(3)	yes(3)
5b	NQ - diamond coring	rotary/wireline	no	yes(3)	yes(3)	yes(3)	yes(3)
5c	HQ - diamond coring	rotary/wireline	no	no	yes(3)	yes(3)	yes(3)
5d	BW44- diamond coring	rotary/conventional	n/a	n/a	n/a	n/a	n/a
5e	BV double - diamond core barrel	rotary/conventional	n/a	n/a	n/a	n/a	n/a
5f	BV - triple - diamond core barrel	rotary/conventional	n/a	n/a	n/a	n/a	n/a
5g	NV -double - diamond core barrel	rotary/conventional	n/a	n/a	n/a	n/a	n/a

5h	NV- triple - diamond core barrel	rotary/conventional	n/a	n/a	n/a	n/a	n/a
5i	3.0" Christensen Marine Barrel	rotary/wireline	no	no	yes	yes	n/a
5j	3.11" rotary corer	rotary/wireline	no	no	yes	yes	n/a
5k	Geobor S corer/pilot corer	rotary/wireline	no	no	no	no	yes

Notes:

1. Sea floor reaction frame is required for operation
2. Submerged unit weights are based on the ID of the tool joint being bored to accept geotechnical tools
3. If proper stabilization is provided inside of outer string
4. May not be compatible with other systems

Table 4.2. Comparison of Samplers Available for Various Mining Flush Joint Casing Sizes

Item	Description	Sampling	Steel Mining Style Flush Joint Casing(2)				
		Method	BW	NW	HWT	CHD 101	CHD 134
1	**Dimensions of Flush Joint Casing**						
1a	OD tube body, inches	n/a	2.875	3.5	4.5	3.701	5
1b	ID tube body, inches	n/a	2.375	3	4	3.268	4.5
1c	OD tool joint, inches	n/a	2.875	3.5	4.5	3.701	5
1d	ID tool joint, inches	n/a	2.375	3	4	3.091	4.125
1e	submerged weight/ft(note 2)	n/a	6.09	7.5	10.1	7.65	12.2
1f	normal bit size, inches	n/a	2.98	3.782	4.827	4.5	5.5
1g	typical core size	n/a	N	H	P	H	P
2	**Soil Samplers**						
2a	2 1/4" thin walled shelby tube	push	no	yes	yes	yes	yes
2b	2" split spoon	percussion	no	yes	yes	yes	yes
2c	2 1/4" liner sampler	push	no	yes	yes	yes	yes
2d	2 14" thick wall taper tube	percussion	no	yes	yes	yes	yes
2e	3" thin wall shelby tube	push	no	no	yes	no	yes
2f	3" piston sampler	hydraulic	no	no	yes	no	yes
2g	3" thick wall taper tube	percussion	no	no	yes	no	yes
2h	3" piston liner sampler	hydraulic	no	no	yes	no	yes
2i	2.2" rapid piston sampler	hydraulic	no	no	no	no	yes
2j	2.05" Pilot rotary corer	rotary	no	no	no	no	yes
2k	1.5" split tube sampler	percussion	yes	yes	yes	yes	yes
2l	1.625" swelling soil barrel	push	yes	yes	yes	yes	yes
2m	165 lb wireline percussion hammer	percussion	no	yes	yes	yes	yes
2n	300 lb wireline percussion hammer	percussion	no	no	yes	no	yes
2o	Geobor S shelby tube	push	no	no	no	no	no
3	**In situ testing/speciality tools**						
3a	umbilical type CPT/PCPT	hydraulic push(1)	n/a	n/a	yes	n/a	yes
3b	Dolphin Remote vane	push	n/a	n/a	yes	n/a	yes
3c	Dolphin CPT/PCPT	hydraulic push(1)	n/a	n/a	Possible-3	n/a	Possible-3
3d	2.2" hydraulic hammer sampler	hydraulic hammer	n/a	n/a	possible	n/a	possible
4	**Boart Longyear Geo-Barrel**						
4a	2" push	push	n/a	yes	yes	yes	yes
4b	3" push	push	n/a	no	yes	no	yes
4c	2.155" pilot corer	rotary/wireline	n/a	yes	yes	yes	yes
4d	2.937" pilot corer	rotary/wireline	n/a	yes	yes	no	yes
4e	3.345" hard rock core	rotary/wireline	n/a	yes	yes	no	yes
4f	2.5 " hard rock core	rotary/wireline	n/a	yes	yes	yes	yes
5	**Hard Rock Coring Systems**						
5a	BQ - diamond coring	rotary/wireline	yes-4	yes-4	yes-4	yes-4	yes-4
5b	NQ - diamond coring	rotary/wireline	yes-4	yes-4	yes-4	yes-4	yes-4
5c	HQ - diamond coring	rotary/wireline	no	yes-4	yes-4	yes-4	yes-4
5d	BW44- diamond coring	rotary/conventional	n/a	n/a	n/a	n/a	n/a
5e	BV double - diamond core barrel	rotary/conventional	n/a	n/a	n/a	n/a	n/a
5f	BV - triple - diamond core barrel	rotary/conventional	n/a	n/a	n/a	n/a	n/a
5g	NV -double - diamond core barrel	rotary/conventional	n/a	n/a	n/a	n/a	n/a
5h	NV- triple - diamond core barrel	rotary/conventional	n/a	n/a	n/a	n/a	n/a
5i	3.0" Christensen Marine Barrel	rotary/wireline	n/a	n/a	n/a	no	yes
5j	3.11" rotary corer	rotary/wireline	n/a	n/a	n/a	no	yes
5k	Geobor S corer/pilot corer	rotary/wireline	no	no	no	no	no

Notes:

1. Sea floor reaction frame is required for operation

2. Drill rods have the following dimensions:

Item	Description	Conventional Drill Rods			Wireline Drill Rods		
1	**Mining Rod Dimensions**	BW	NW	HW	BQ	NQ	HQ
1a	OD tube body,in.	2.125	2.625	3.5	2.19	2.75	3.5
1b	ID tube body.in.	1.75	2.25	3.06	1.81	2.375	3.06
1c	OD tool joint,in.	2.125	2.625	3.5	n/a	n/a	n/a
1d	ID tool joint,in.	0.75	1.375	2.375	n/a	n/a	n/a
1e	submerged weight/ft	3.65	4.7	7.4	3.48	4.52	6.7
1f	core size,in.	1.32-1.601	1.875-1.99	2.406-2.5	1.32-1.601	1.875-1.99	2.406-2.5

3. Depending upon burst pressure of tubular used
4. If proper ID stabilization is provided inside of the outer string
5. Range of core sizes represents whether a triple tube is used or thin kerf diamond bit.

Table 4.3. Typical Hole and Core Sizes for Existing Diamond Coring Systems

Operator/Type	SYSTEM Designation	Core Size, in.	Hole Size, in.	Ratio Hole/Core	Bit Kerf	Notes
Mining	AQ	1.062	1.89	1.780	0.414	
Mining	AQTK	1.202	1.89	1.572	0.344	
Mining	BQ	1.433	2.36	1.647	0.4635	
Mining	BQTK	1.601	2.36	1.474	0.3795	
Mining	NQ	1.875	2.98	1.589	0.5525	
Mining	HQ	2.5	3.782	1.513	0.641	
Mining	PQ	3.345	4.827	1.443	0.741	
Mining	BQ3	1.32	2.36	1.788	0.52	
Mining	NQ3	1.775	2.98	1.679	0.6025	
Mining	HQ3	2.406	3.782	1.572	0.688	
Mining	PQ3	3.27	4.827	1.476	0.7785	
Mining	CHD76	1.712	2.98	1.741	0.634	
Mining	CHD101	2.5	3.99	1.596	0.745	
Mining	CHD134	3.345	5.276	1.577	0.9655	
DOSECC		2.312	5.5	2.379	1.594	
ODP	RCB	2.312	9.875	4.271	3.7815	
ODP	DCB	2.312	7.25	3.136	2.469	
ODP	ADCB/PQ	3.345	7.25	2.167	1.9525	1
ODP	ADCB/PQ3	3.27	7.25	2.217	1.99	1
FUGRO	CHRISTENSEN MARINE BARREL	2	8.3875	4.194	3.19375	

Notes:
1. Sea trials schedules for Nov. 2000

Table 4.4. Summary of Sediment Sampling and Coring Equipment

1. Shelby Tube and Liner Sampler

The primary type of soil sampling barrel is a **Shelby tube** sampler for soft sedimentary formations. This is a thin-walled tube that is pushed into the formation. It normally has a ball-check valve at the top to create a suction force to prevent the sample from sliding out when being retrieved. Normally, there are no **core catchers** for this type of barrel. A slightly thicker walled sampler but with a nose cone and basket catcher is also available. This **liner** sampler can be adapted with a lexan or other type of **liner** material if the sediment is extremely soft. These samplers are pushed into the formation with the weight of the drill string using a specially designed latch/paw arrangement compatible with the **bottom hole assembly** or bit.

2. Split Spoons and Taper Tubes

A split-spoon sampler can be used for denser material like sands, silts, and gravels. A split-spoon sampler is similar in some ways to a conventional sampler but split along its length. Sand has a much higher coefficient of friction so it cannot be extruded from a thin-walled sampler in the same manner as a typical clay sample. Split spoons are normally driven into the formation with a downhole, wireline-operated sliding hammer. The number of hammer blows per increment length of sampler has been correlated in a relative sense to the density of the *in situ* material. This sampler has upper and lower caps/shoes so that when removed from the split spoon, the barrel can be split opened revealing the sample. Several sizes of split spoons are available as well as types of core catchers for these barrels. Heavy walled taper tubes are also available and operated with the same type of downhole hammer. These samplers can be driven into extremely hard clays unlike the thinner **shelby tube** samplers that tend to get the attachment holes ripped out upon withdrawing from the formation.

3. Piston Samplers

There are several **piston samplers** available but these usually reside in the suite of *in situ* testing tools since they require a seafloor reaction mass. The reaction mass is necessary to isolate vessel motion in order to provide the high quality of sample necessary for the geotechnical investigation of foundation design to be performed. This sample is normally pushed into the formation at a controlled rate of speed at 2 cm/sec. The piston not only helps draw the material into the barrel during the down stroke but also prevents additional material from being sucked into the tube on the withdrawal.

4. Advanced Piston Samplers

The Ocean Drilling Program (ODP) developed an Advanced Piston Corer (APC) which is fired into the formation. This sampler is approximately 30 ft long and operates on the principle of shearing pins to drive the sampler into the formation with pressure built up inside the drill string. However, because of its length, high levels of over pull are typically experienced when retrieving the barrel. This is normally not a problem with a derrick rated for 1,200,000 lbs as in the case of the JOIDES Resolution. However, most portable geotechnical rigs do not have the rated derrick capacity or height to operated such a long sampler. As a comparison, typical thin-walled samplers used in the geotechnical community are normally less than one meter in length.

5. Mini Advanced Piston Samplers

A small version of this type of APC sampler was also developed by the ODP for a mining coring system. This system can be interchanged with the core barrel should sediments be found which can not be cored. This type of sampler can be built for any of the drilling rig type operations using H size core barrel (2.5" OD). It is possible that this type of **piston sampler** can be designed for N size core barrels (1.875" OD) as well. This **APC** sampler is not widely known in the geotechnical or drilling contractor arena and most likely would have to be developed by the specific contractor, if required for a coral drilling program. The mini-APC developed by ODP can adapt up to a 5 ft long sampling barrel and can vary the force to thrust the barrel into the formation by changing the number of shear pins along with material type.

6. Geo-Barrels

Several of the companies that manufacture diamond core barrels offer what is referred to as a “Geo-Barrel”. This is basically a hard rock diamond core barrel that adapts a push sampler, extended nose core barrel, and full-hole drilling with the introduction of a roller cone bit. A particular extended nose barrel is called **punch corer**. Here the nose is spring loaded in order to retract back into the outer barrel should harder formations be encountered. This core barrel has advantages in granular material. These “Geo Barrels” comprise a versatile system but are only offered in an H size (2.5" OD) system or larger. The mini-APC was developed to be interchangeable with these tools.

7. Diamond Core Barrels

Diamond core barrels offer another solution for obtaining high recovery samples in difficult material types. Materials typically need to be semi-consolidated, but with a good mud program, loose materials have been cored as well. Most mining style core barrels offer either double or triple tube options and utilize thin **kerf** diamond bits. The inner core barrel is mounted on a swivel so that the incoming core does not rotate as it enters the barrel. Core is broken at the conclusion of a core run with a collet-type core catcher. Basket-type catchers are also available and can be run in tandem with a collet catcher if loose or broken material is expected to be encountered.

Table 4.5. Potential Platforms for Conducting Geotechnical Sampling/Coring Operations

Vessel/platform Type	Water Depth, m	Rig Config.	Total Depth (m) or Capacity (mbsf)	Rig/Corer Type	Pipe/ Rods	Anchoring/ Positioning	Riser Required	Heave Comp.
portable flexi-float	3 to 30	M/C	< 300	mining rig or portable	API/ mining	4-point	possible	Maybe
work barges	5 to 100	C/C	300 to 600	mining rig or portable	API/ mining	4-point	possible	Maybe
special design drilling barges	5 to 200	M	< 800	mining rig or portable	API/ mining	4-point /DP	possible	Maybe
small seabed frame (diver assist)	0 to 20	n/a	10 to 30 mbsf	mining rig	mining	seabed	none	No
small seabed frame	< 2000	n/a	6 mbsf	mining rig	mining	seabed	none	No
seabed frame	10 to 2000	n/a	5 - 100 mbsf	mining rig	mining	seabed	none	No
very small lift barge	0 to 20	C	30 to 100	small mining rig	mining	lift legs	possible	No
small self elevating barge	10 to 60+	CL	< 1000	portable/mining rig	API/ mining	lift legs	probable	No
oil field jack up	20 to 100+	C/C	< 1000	fixed portable/mining	API/ mining	lift legs	probable	No
small work vessel < 30m	<100	CL	< 300	small portable/mining rig	mining	4-point	probable	Yes
research/survey/work vessel < 60m	225 to 365	M/C/C	< 350/1000	mining/portable rig	API/ mining	4-point	API as riser	Yes
research/survey/work vessel < 60m	20 to 1500	M/C/C	> 650/1500	mining/portable rig	API/ mining	DP	Plastic as riser	Yes
Geotechnical drillship	< 330	M	< 600	fixed derrick	API	4-point	no	Yes
Geotechnical drillship	<1500	M	1650 (note 4)	fixed derrick	API	DP	no	Yes
Geotechnical drillship w/ piggy back	<1500	M	1000 (note 5)	fixed w/mining rig	API/ mining	DP	API as riser	Yes
Science drillships	50 to 7000	M	< 7000	fixed derrick	API	DP	no	Yes
Oil Field Semi submersibles	50 to 3000	M	< 3000	fixed or portable rig	API	DP	API as riser	Yes

Notes:
1. M refers to moonpool
2. CW refers to centerwell
3. CL refers to cantilevered unless noted
4. Without using aluminum pipe
5. Depth limitations of HQ piggy-back coring system
6. A portable rig is designated as a rig that uses API style drill pipe
7. Mining/Mineral Rig is designated as a rig that used mining style drill rods

Table 4.6. Comparison of Typical Drilling Options Available for Submerged Coral Drilling Operations

Item	ODP	Typical North Sea Geotechnical Vessel	Small mining/ mineral type rig
Total depth capability, m for HQ size core	<7000 n/a	<1650 <1000	<1500 <800
Drilling type heave compensation	yes	available on some ships	yes
Accuracy	Depends on water depth & string stiffness ('+/- 7.5k)	hard tie system simulates land drilling <1k	very sensitive & accurate <1k
Coring system available	RCB ADCB	Christensen Marine Barrel HQ and possible BQ	HQ/NQ/BQ
Typical % recovery	15- 30%+ for RCB High recovery for ADCB?, but dependent upon AHC	30-60% for Christensen Marine Barrel 60-90%+ for piggy back HQ	80%+
Riser	no	yes	yes
Mud returns	no	no	depends on water depth/system
Pipe size	API w/ upset tool joints	API w/ upset tool joints mining string w/ flush joints	mining string w/ flush joints
Vessel duration	<60 days	<30 days	<30 days
Accommodations	<120	<46	<40
Onboard science laboratory	extensive	very limited	very limited
Seafloor template	no	yes	depends on water depth/system
RPM	<120	<120 for API <1000 f/ mining string w/ riser	<1200 w/ riser
Casing size available	20/16/13, 3/8/10, 3/4	API drill pipe	PQ/HQ/NQ rods
Interchangeable tools for diamond system Logistics	not at this time very good logistical established	no, but may be added must be set up f/ specific job awarded	yes, but not developed by contractors must be set up f/ specific job awarded
Time to establish start up program	must follow existing science protocol <2 yrs	<6 months could be performed much quicker once placed on schedule	<6 months could be performed much quicker once placed on schedule
Costs	Turn-key operation once proposal placed on schedule	medium to high, depends on ability to perform back to back projects, location, water depth, etc.	low to medium, depends on ability to perform back to back projects, location, water depth, etc.

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Appendix 2: Glossary of Geotechnical Terms

Active Heave Compensator – A compensator that uses accelerometers or other types of data input to actively drive the hydraulic cylinder. The AHC is more accurate than a passive compensator and maintains better weight on bit control.
ADCB – Advanced Diamond Core Barrel. ODP's new core barrel, which cuts a PQ/PQ3 size core (3.345"/3.27") while maintaining an outer hole diameter of 7.25". The ADCB uses rotary shouldered connections (API) and does not require a riser for operation.
A-frame – A large frame normally attached the stern of a vessel. The A-frame is used to launch and recover seafloor operated coring templates.
API- American Petroleum Institute. Sometimes referring to the larger upset tool joint style of pipe used by most oil drillers.
Assisted moored – A four-point vessel requiring assistance from another vessel to run its anchor spread.
Basket catcher – A full closure finger-type of core catcher used for loose or granular material. Core catchers are used inside of core barrels and other types of geotechnical samplers.
BHA- Bottom Hole Assembly. Typically refers to the core barrel and whatever additional drill collars or transition joints before crossing back the standard drill pipe or rods.
Cantilever – Usually refereed to a type of position that the drilling rig is placed over the side of a vessel.
Casing – Structural tubing/pipe used to prevent the formation from collapsing and/or to assist in mud re-circulation.
Centerwell – A large well through the hull of a vessel through which a guide base or ROV might be deployed.
Core catcher – A device used to break and capture the core or sample.
Day rate – The daily rate (24 hr) paid a contractor for a specific piece of equipment, equipment spread, or personnel. It may be inclusive of broken down into transit, standby, working, and downtime rates.
Demob – Demobilization of equipment at the completion of a job. It may be defined as a lump sum amount or day rate.
Derrick – The structural framework or tower portion of a drilling rig that encompasses the hoisting equipment and/or rotary mechanism used to rotate the drill pipe/rods.
Double tube core barrel – A core barrel consisting of an outer tube and inner non-rotating tube in which core is collected.
Drawworks – The hoisting equipment portion of a drill rig.
Drill Collar – The large heavy weight tubular that is used to provide weight and strength to the BHA.
Drilling fluid/mud – The fluid that is circulated through the bit to both clean the hole of cuttings and keep the bit cool
Drill Pipe – Tubular lengths of pipe that have upset tool joint. Usually referring to API type of drill pipe.
Drill Rods – Tubular lengths of thin walled pipe with flush ID and OD connections. Drill rods are most commonly used in mining and mineral exploration.
Dynamic Positioning System – A computer controlled system that maintains a vessels position while drilling an offshore well.
Environmental concerns – Issues relating to the hazards of drilling that might occur to the environment.
Four point spread – A designation of using four anchors at each corner of the vessel to hold position while drilling.
Guide line tensioner – Typically large oil over air cylinder that has been adapted to a passive heave compensator for a portable drill rig.
Hard tie system – A system using a passive compensator that connects a seabed template/guidebase to the vessel so that real time heave compensation can be provided for in situ geotechnical tests.
Inner core barrel – The inner portion of a core barrel that collects the core. It may be wireline retrievable or fixed.

Impregnated diamond bit – A bit that is manufactured with different sizes of diamond grit housed in a matrix. As the bit is advanced, the matrix wears away exposing new, sharp diamonds.
Jack up rig – A large self-elevating platform usually designed with a drilling derrick for Oil & Gas exploration.
Kelly drive – A drill rig with a rotary table, that uses a hexed or keyed rod to transmit torque to the drill string.
Kerf – The thickness of the bit face as measured by subtracting the OD from the ID and dividing by two.
Liner – A device used in core barrels or sample tubes to collect soft, granular, or friable material. It may be manufactured from plastics or metals.
Mob – Mobilization of equipment at the start of a job. It may be defined as a lump sum amount or day rate.
Moonpool – A small diameter pipe (18"- 48") installed through the hull of a vessel to allow drilling operations to be performed from the deck of the vessel.
Mud system – The motors, pumps, centrifuge, and mud tanks used for mixing, storage, and settling out of mud for drilling/coring.
Multi leg/site program – A drilling program that combines several different jobs and/or sites which may benefit financially from shared mobilization/ demobilization costs.
Nested casing system – A series of casing which stack neatly inside of one another. It is usually used in a telescoping type scenario starting with the larger casing and working down to the smallest with depth. Diamond core rods are designed to nest inside one another so that once a rod size cannot be drilled deeper, it becomes the casing for the next smaller size of core barrel/rods.
Outer core barrel – The outer portion of the core barrel that is connected to the drill rods/BHA. It is usually stabilized with diamond pads to help maintain hole diameter and drill string stability.
Overshot- A device used to catch the sampler/core barrel and recover it to the surface via wireline.
Passive Heave Compensator – A compensator that relies upon air pressure to hold up the amount of weight the driller does not want felt at the bit. The PHC is less accurate than an active compensator. Bit weight fluctuations are larger than an AHC and bit lift off may occur under certain circumstances.
Pennant line – A line attached to a preset anchor and marked with a buoy. Pennant lines/anchors may be preset which allow a vessel to work in deeper water than it normally is capable of when operating in a self-mooring situation.
Percussion sample – A wireline sampler that uses a down hole hammer to drive a shelby tube of split spoon into a dense formation.
Piggyback system – The operation of a small diamond-coring rig in conjunction with a larger fixed derrick geotechnical drillship. The smaller diamond rig is placed atop the open spindle top drive and allows the rods to be inserted through the API string that is now serving as a riser.
Piston sampler – Typically a thin walled shelby tube sampler that utilizes a piston in the throat of the shelby to reduce sample disturbance during both insertion and withdrawal.
POOH – Acronym for pulling out of the hole with pipe.
Push sample – Usually a thin walled sample tube which is pushed into soft to stiff clay/silt formations.
Punch corer – A type of core barrel inner tube which is used to sampler granular type material that might normally be washed away by fluid flow when coring. The punch corer has an extended nose cone that protrudes in front of the bit and is spring loaded to retract back into the outer should harder formations and/or layers be encountered.
RIH – Acronym used for running in the hole with pipe
Riser – A tubular member that is used through the water column to support the thin walled mining rods from connection failure while rotating at high RPM's. It can also be used as a conduit to re-circulate drilling fluids.
ROP – Acronym used for Rate of Penetration of a drill bit. It is usually designated as m/hr or in/min.
Seafloor clamp – A hydraulic clamp attached to a seafloor template or guide base used to grip the drill pipe and isolate any movement when performing an in situ geotechnical test.
Seafloor Template/Guidebase – A structural framework that is lowered to the seafloor either by wire rope or the drill string itself. It function is to provide re-entry capabilities or a support a seafloor clamp for in situ testing or both.
Self-elevating barge - A small self elevating platform usually designed with a clear deck for servicing shallow Oil & Gas wells or for construction purposes. It provides an ideal platform for installing a

portable drilling rig for offshore work. Drilling operations that employ a jack up barge can emulate onshore drilling operations and thus do not require a heave compensator.
Self moored – A four-point vessel that does not require assistance from another vessel to run it's own anchor spread.
Semi submersible – A self propelled drilling platform that is partly submerged upon arriving on site to lower the center of gravity and provide a more stable platform from which to drill.
Shelby tube – A thin walled sampler usually for collecting undisturbed fine-grained material such as clay. Used in the geotechnical industry for soil sampling.
Shipping container – A standard steel size crate in which many drilling contractors have design their drilling systems to fit into or be part of. Typical containers are available in 10', 20' and 40' lengths.
Single tube core barrel – A core barrel that collects the core without an non rotating inner barrel.
Slim hole technology – Typically refereed to as mining drilling operations that employ rods that are flush OD and ID and where each next smaller size rod nests into the previous size rod.
Slip joint – A telescoping joint of pipe typically used to compensate a riser for heave and or tide variations.
Spindle drive – A small drill rig that uses a rotary chuck to clamp onto the drill rod itself and provide the rotation to advance the core barrel.
Splits – Refereed to as the metal split liners used as the triple tube inside a core barrel.
Supply vessel – A vessel of opportunity which has a clear deck and may be used for drilling operations if it has a moonpool/centerwell and/or a 4 point/dynamic position system.
Surface set diamond bit – A diamond core bit employing a larger sized diamond or synthetic cutter which is usually operated at a slower speed than an impregnated diamond bit.
Thruster – Usually a propeller device that is either lowered beneath the hull of the ship or built into the hull to provide a means of maneuvering the vessel. Thrusters are employed when the vessel is held on station by a dynamic positioning system.
Top drive – A drill rig that uses a hydraulic device to rotate the pipe. The top drive is connected to the top of the drillstring and is lowered down the derrick as the pipe is drilled into the formation.
Tool joint – A steel upset rotary shouldered connection used to joint API pipe together.
Total depth capacity – Total depth capacity is refereed to the water depth plus depth beneath the seafloor that a drilling rig is rated with a certain weight or drainpipe/rod.
Triple tube core barrel – A core barrel employing a third tube or liner to capture the core.
Uni-BHA – A bottom hole assembly which allows for a suite of different coring/sampling tools to be operated in without having to pull the bit/BHA to make changes for a different type of sampler.
Vessel of opportunity – A vessel located in a port facility that is close to the location of study that can be leased for the duration of the job.
Vibrocorer – An electrical or pneumatic device used to vibrate a sample tube into the seafloor from a seabed mounted frame.
Wireline – Referring to the type of sampling/coring that allows the inner barrel or sampler to be withdrawn via wireline.
Wireline hammer – A downhole hammer operated on the surface by a wireline.
WOB – refers to weight on bit.