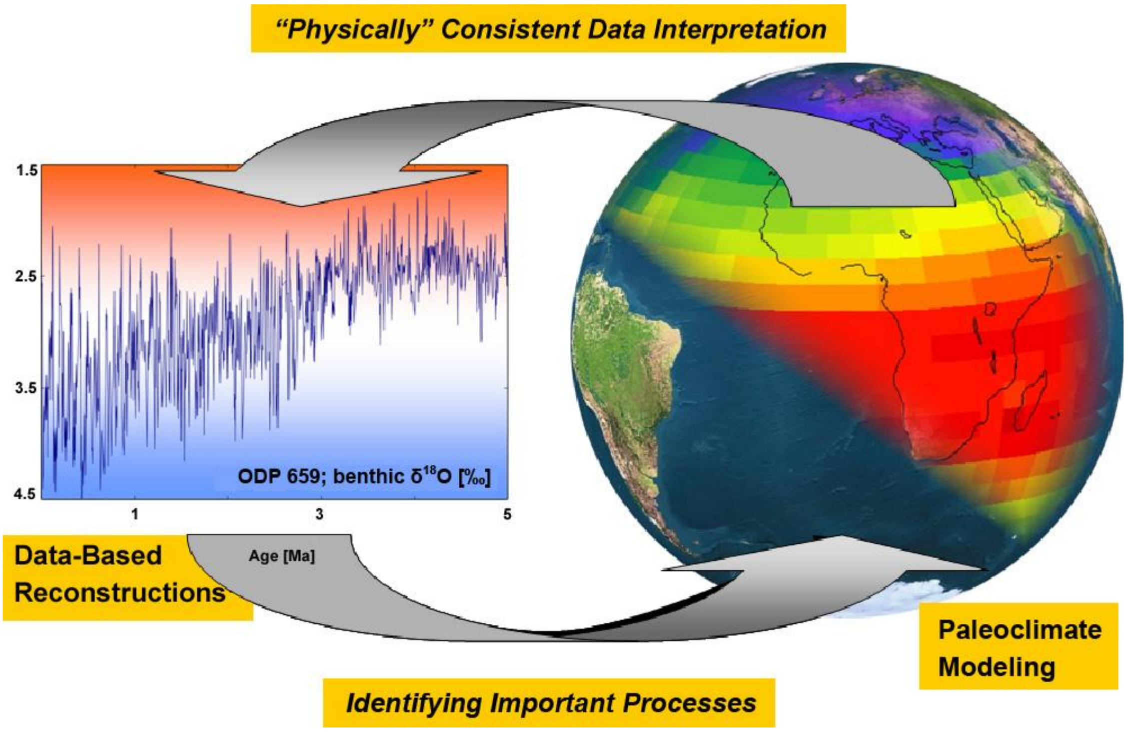
Thematic Review

Report Series No. 1

Understanding Climate Variability by Scientific Ocean Drilling

A Mid-term Review of IODP Achievements 2002-2005



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Front cover: Paleoclimate modeling to decipher past climate dynamics. (from Tiedemann et al., 1994).

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Executive Summary

Background

Environmental Change, Processes and Effects is one of the major three research themes of the Integrated Ocean Drilling Program (IODP) Initial Science Plan (ISP). Within this theme, 'Extreme Climates' and 'Rapid Climate Change' (i.e., climate variability) were named special research initiatives, both with strong links to changes in global sea-level. An IODP thematic review panel on climate variability met for two days in August 2007 and briefly again in December 2007. It reviewed three IODP projects comprising the four expeditions (302, 303/306 and 310) out of the 12 IODP expeditions conducted during the years 2004−2005 and prior to the IODP drilling hiatus 2006−2007. The panel also briefly reviewed six expeditions planned (as of end 2007) for implementation during 2008−2009. The peak of post expedition research typically occurs around 3−4 years post expedition, and inclusion of publication metrics was therefore deemed premature and are not included in the review.

The IODP provides significant advances over Ocean Drilling Program (ODP) including the addition of mission specific platforms (MSP's), allowing exploration of the Arctic Ocean, shallow water and reef environments and offering new high-resolution core imaging and scanning technology. Benefiting from these advantages, IODP during its first drilling phase 2004−2005 successfully further augmented the research fields of paleoceanography and paleoclimatology with results that reached world news headlines and top-ranking scientific journals. Overall, IODP achievements in this research area have been impressive and should form a strong basis for continued, if not increased, deliberations in an area with obvious tie to global warming research. During IODP, the Intergovernmental Panel on Climate Change (IPCC) has acknowledged scientific ocean drilling data to provide important (paleo)climate data of importance for modeling of future global warming and its effect on the Earth and its habitability.

The predecessors to IODP, the Deep Sea Drilling Program (DSDP) and the ODP, made fundamental contributions to generate the research field of paleoceanography and its legacy holdings (in IODP custody) continue to form an important research basis. However, only findings based strictly on IODP drilling have been included for review in this report.

Specific Achievements

Specific achievements were reviewed with reference to the following sub-themes: (1) Extreme Climates, (2) Rapid Climate Change, and (3) Internal and External Climate Forcing and Sea-level Changes.

Extreme Climate:

- Discovery of the strong impact of the Paleocene-Eocene Thermal Maximum (PETM) into the high Arctic with sea surface temperatures (SST) possibly as high as 20-25°C.
- If such high SST represent regionally valid annual averages, very low temperature gradients between high and low latitudes.

- The presence of seasonal Arctic sea ice in the mid Eocene (~45 Ma) relatively shortly after the presence of high SST is suggested by debris interpreted as ice rafted debris (IRD).
- Permanent or semi-permanent ice cover in the Arctic from about 14 Ma.

Rapid Climate Change:

- Multiple, long and continuous cores from North Atlantic high sedimentation rates (7-17 cm kyr^{-1}) drift deposits providing critical information on changing surface water hydrography, ice sheet-ocean interaction, and deep-sea circulation on millennial time scales well beyond the last glacial cycle and throughout the Pleistocene.
- Prominent Heinrich events from the last glacial period readily identifiable in density, magnetic susceptibility, and scanning XRF record and are found prior to the last glacial cycle as far back as 650 ka.
- Millennial-scale variability during the Pleistocene as orbital and glacial boundary conditions changed; significant differences existed in millennial climate variability between the last and penultimate glaciations (MIS 6).
- Strong link between iceberg discharge and weakening of Atlantic Meridional Overturning Circulation (AMOC) suggesting an ice volume threshold mechanism for rapid climate changes.
- Improved stratigraphic framework for the Pleistocene from combined oxygen isotope and relative geomagnetic paleointensity data furthering regional to global marine correlation, and for linking to lake sediments and polar ice cores.
- Recovery of massive corals offshore Tahiti revealing past sea-surface temperatures at seasonal resolution between 16 and 8 kyr and allowing for detailed investigations of variations in the El Niño-Southern Ocean Oscillation (ENSO) during this time interval.

External and Internal Forcing and Sea-level change:

- Excellent North Atlantic material to address climate variations at Milankovitch, millennial, and centennial-to-decadal timescales.
- Opportunity to distinguish between (known) cyclicity in external forcing (orbital forcing) and other parameters (e.g. surface-water hydrography, deep-water circulation, and ocean-cryosphere interactions during glacials and interglacials.
- Detailed and continuous sea-level curve for the last deglaciation from the Western Pacific (Tahiti) including melt-water pulse 1A (MWP).
- Antarctic and Northern Hemisphere ice sheets suggested to have acted in concert during the last deglaciation.
- Questioning previously proposed reef drowning events caused by exceedingly rapid global sea-level rise (20m kyr^{-1}) during the last deglacial.

In addition, significant operational and analytical achievements (e.g. mission specific platforms, core logging, digital imaging, and XRF scanning) have been made. This has allowed drilling in challenging environments (e.g. Arctic, shallow carbonate reefs), and rapid non-destructive determination of changes in physical properties and elemental composition.

Shortcomings

An stratigraphic hiatus (~44-18 Ma) within the cored section in the Arctic Ocean, and the loss of some potentially very high-resolution sediment drift sites in the North Atlantic due to weather limitations presents the most notable shortcomings in terms of core and data recovery. Of more broad programmatic importance, the review panel notes that hardly any drilling efforts have been made (some are planned) in the area of internal forcing of climate change (i.e., mountain uplift, oceanic gateways, Large Igneous Provinces). Similarly, investigations of the carbon cycle and its relation to climate change are (largely) absent from both past and planned IODP experiments. These shortcomings for the large part reflect limited drilling time, and to a lesser degree weak proposal pressure. IODP has improved integration with International Continental Scientific Drilling Program (ICDP), including lake drilling, but less so with other and related programs (e.g. IMAGES, ANDRIL). However, these collaborative efforts potentially would benefit from the inclusion of coordinated experiment design and data dissemination.

Conclusion and Recommendations

Four expeditions were spent on the research field of climate variability and related sea-level change during the 12 expeditions of IODP Phase 1. These four expeditions truly broke new ground in terms of drilling strategy (strategic arrays of high-resolution sites), environment (ice infested waters and carbonate reefs), methodology (e.g. high resolution scanning and magnetic paleointensity) and by successfully sampling the last unexplored ocean basin (Arctic Ocean Basin). Drilling results from the latter perhaps made the strongest public impact ever of ocean drilling and so far have generated five papers in the journal *Nature*. Potential gains from a revisit to the Arctic Ocean basin should be carefully evaluated.

The high-resolution paleoceanographic records obtained have significant potential for constraining causes, effects and rates of rapid climate and sea-level change, providing links other programs (e.g. ice coring and lake drilling) and communities, and has obvious societal relevance. IODP is recommended to carefully monitor its position and progress made in the field of rapid climate change and how IODP data might underpin the efforts by the IPCC to determine future global change (e.g. rate of sea-level change during recent deglacial periods or sea level during the mid-Pliocene warm period). We also recommend to reach out to other related programs, involve as much as possible interdisciplinary approaches and modeling from planning of sites through interpretation and dissemination of drilling results in order to scientifically optimize experiments. Investigations of potential linkages between the deep biosphere, the carbon cycle and climate at various time scales and time periods should also be carefully considered.

The review panel recommends the research theme of climate variability to be given a high priority the coming years. There are no indications that the field yet has reached a mature stage with reduced potential for scientific return. Its societal relevance and impact is obvious. New prospective analytical techniques and experiment designs may require revision of sample policies, mores cores to be sampled at each site, and revisits to legacy sites to obtain new and unsampled continuous cores from critical locales and intervals.

1. Introduction and Background

Environmental Change, Processes and Effects is one of the major three themes of the IODP Initial Science Plan (ISP). Within this themes the 'Extreme Climates' and 'Rapid Climate Change' (both with strong links to sea-level change), were named special research initiatives of the ISP. Following the writing of the ISP around year 2000, the trend of global warming has become increasingly tangible, and is now widely considered to pose a major future environmental and societal challenge of geopolitical significance. There is particular public and political focus on the role of anthropogenic greenhouse gases as a driver for the observed warming trend. IODP findings within paleo-climate research has therefore gained strong societal interest and were recently recognized by the IPCC (2007) as an important contributor to understand processes of climate change. The two specific research initiatives chosen included in the IODP ISP, 'Extreme Climates' and 'Rapid Climate Change' (and related sea-level changes) are highly relevant in terms of assessing: (1) what extremes might be possible for our planet and their implications for future climate change, (2) how rapid major changes in climate and sea-level have happened in the past, and (3) critical parameters and thresholds in Earth systems affecting climate change. The IODP has decided to make its first review of scientific achievements in climate variability in order to map out how future scientific priorities matching the rapidly growing need for understanding climate change at human and longer time scales could be set.

While drilling data only rarely resolve climate variations at societal time scale (i.e., interannual to interdecadal), some records have now demonstrated frequent resolution at centennial to millennial time scales, and occasionally decadal or better (Santa Barbara Basin, Cariaco Basin, etc.). Instrumental climate and ocean data provide a record of decadal and shorter-term variability over the past one hundred or more years. Ice coring can provide climate proxies at high resolution back to a few hundred thousand years, and at somewhat lower resolution back to around 800 ka. However, to extend our record of climate change to the oceans, and further back in time entirely depends on information retrieved from the marine geological record. Conventional piston and gravity cores from the ocean basins provide high-resolution climate and ocean records of the past glacial cycle, but are limited in temporal extent or resolution (e.g. kyr for the older record). Only long continuous drill cores from below the oceans and those of long lived lake systems can provide a complete temporal sampling on scales ranging from (sub)millennial to tens of millions of years. Drill cores allow us to study periods during which the Earth experienced significantly different and extremely warm climates with much reduced, or no bi-polar glaciation. Ocean (and lake) drill cores provide spatial coverage from the equator to the pole, illuminate land to sea linkages and evaluate the role of land-ocean-atmosphere carbon cycle in climate change.

This review builds on three dedicated research experiments comprising four IODP Expeditions conducted in the field of climate variability during the initial IODP expedition years 2004 and 2005: IODP Expedition 302, 303/306 and 310. Following a drilling hiatus in IODP during 2006-2007, up to six more expeditions in this field are planned for implementation during 2008−2009, and briefly commented on in this review. In examining the scientific results of the 2004−2005 expeditions, it should be kept in mind that the peak of post expedition research typically occurs around 3−4 years post expedition. At the time of this review (August of 2007), only Expedition 302 had just entered this time interval. No bibliography of publications are therefore included in this review (IODP publications at: http://www.iodp.org/scientific-publications/). It should be noted, however, that the Arctic expedition (Expedition 302) has resulted in five articles in the journal NATURE and a special section within the journal Paleoceanography (Vol. 13, No 1, 2008)(full list of content on http://lookleap.com/agu.org/a1).

The predecessors to IODP, the DSDP and the ODP, made fundamental contributions to generate the research field of paleoceanography. Legacy holdings of cores, samples and data are presently in IODP custody and continue to form an important research basis. In fact, results of late ODP drilling were first published during the current IODP because of the delay between drilling and publication of post expedition research. However, only findings based strictly on IODP drilling have been included for review in this report. This review therefore is not documenting the overall importance of scientific ocean drilling to understand the history and mechanisms of Earth's climate.

Below, we first present a brief summary of results from each of the four expeditions followed later by a review of scientific achievements within the ISP defined themes and initiatives.

2. Summary of IODP Activities

Two out of the four IODP expeditions evaluated here (Fig. 1) comprise a coupled experiment (Expeditions 303 & 306) that used the program platform *D/V JOIDES Resolution* to sample North Atlantic drift deposits. The other two expeditions were conducted with mission specific platforms because of the challenging environments associated with Arctic sea-ice (Expedition 302) and shallow water reef systems (Expedition 310), respectively. Also shown in Figure 1 is the location of planned, but not yet implemented, IODP expeditions in this field of research.

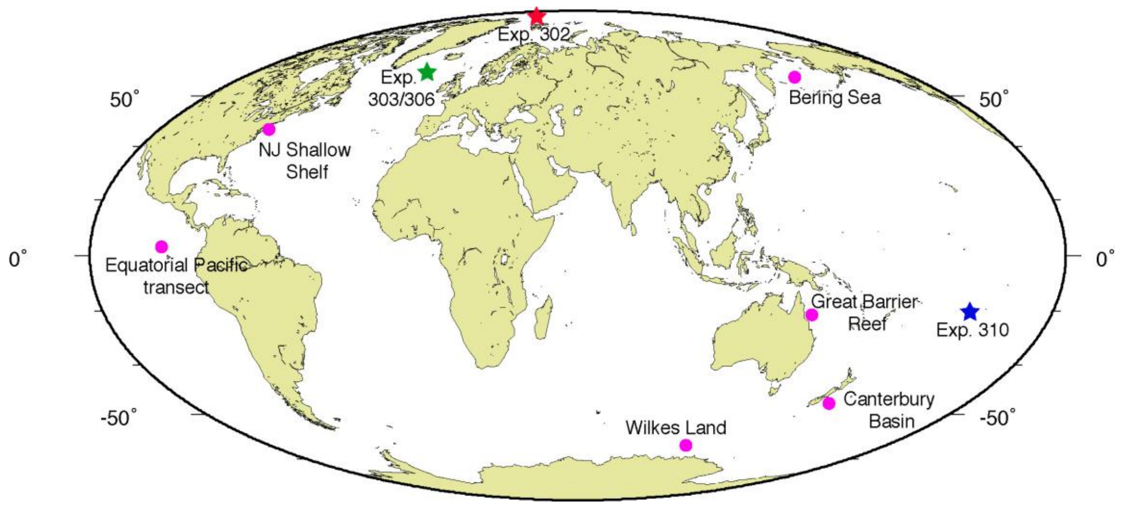

Figure 1. Location of past (stars) and planned IODP expeditions (circles) in the research field of "Climate variability" (including sea-level change).

Expedition 302 – Arctic Drilling

IODP Expedition 302 (Arctic Coring Expedition (ACEX); Backman et al., 2006) was the first IODP expedition to employ a mission specific platform (MSP). Deployment of a fleet of three high ice-class vessels (Fig. 2) allowed the first drilling and sampling deep below the seafloor of the central Arctic Ocean. The main objectives were to understand the long-term (50 Ma) climate history of the central Arctic Ocean, its role in Earth's transition from warmer climate in the Paleogene to the current icehouse world, and the tectonic development of the central Arctic Ocean since the late Paleocene. Many aspects of these objectives were successfully accomplished, including as follows:

1) Highly elevated SST are indicated to have existed near the North Pole, increasing from ~18°C to over 23°C during the PETM (~55 Ma), which implies absence of even seasonal sea ice.

2) Evidence of IRD was detected as early the middle Eocene (~46 Ma)

3) Large quantities of the free-floating fern Azolla grew in the Arctic Ocean by the onset of the middle Eocene epoch (~50 Ma), which included an episodic freshening of Arctic surface waters during an ~800 yr interval

4) The Arctic Ocean at the location of drilling went from an oxygen-poor 'lake stage' at around 50 Ma, to a transitional 'estuarine sea' phase with variable ventilation, and finally to the fully ventilated 'ocean' phase no later than 17.5 Myr ago.

These and other results require future testing and replication, in part in different locations within the vast Arctic basin region, but may eventually lead to a transformational understanding of the Arctic environment and its sensitivity and role in climatic processes, glaciation and pole-ward heat transport. One shortcoming of Expedition 302 was the unanticipated occurrence of a large stratigraphic hiatus (ca. 44-18 Ma) at 198.13 mbsf separating the Neogene and Paleogene intervals. This prevents reconstruction of ocean and climate change during this critical time period of climate cooling. It will require new drilling in stratigraphically more suitable settings to recover this important information and fully address on of the original prime goals of Expedition 302.

Figure 2. Arctic operations (icebreakers *Oden* and *Sovetskiy Soyuz* and the lower left *D/V Vidar Viking)*. Photo by Heiko Pälike.

Expeditions 303/306 – North Atlantic Climate 1 and 2

IODP Expeditions 303/306 built on sections first drilled by DSDP Leg 96 (Channell et al., 2006) allowing the targeting of critical sequences for evaluating North Atlantic climate change with improved recovery, enhanced chronology, and new methods of data analysis. The two expeditions were planned and executed as one single project. Ten sites were drilled from the mouth of the Labrador Sea to the central Atlantic to address the need for long, continuous records of millennial-scale climate variability from the "Ruddiman ice-rafted detritus" (IRD) belt between 40 and 55°N in the North Atlantic (Ruddiman, 1977; Channell et al., 2006). Expedition 303 occupied seven sites and recovered 4656 m of high-quality upper Pliocene–Quaternary sediments. Expedition 306 occupied three sites and recovered 2343 m of sediments.

The high accumulation rates (7-17 cm kyr^{-1}), which characterize the sedimentary sequences recovered by IODP Exp. 303/306, are ideally suited to monitor millennial-scale variations in climate over the past several million years when the amplitude and frequency of climate variability changed substantially. In addition, the water depths of the sites are appropriate for monitoring millennial-scale changes in the properties of lower North Atlantic Deep Water (NADW). Preliminary stable isotopic, core logging, and scanning XRF results indicate the 303/306 sediments contain distinct records of millennial-scale environmental change, including variations in sea-surface hydrography, deep-water circulation, and ice sheet–ocean interactions. The sediments also contain abundant planktic and benthic foraminifera for oxygen isotope stratigraphy and display high-fidelity records of geomagnetic excursions, reversals and relative paleointensity (RPI). The potential exists for developing a high-resolution chronostratigraphic template for North Atlantic climate variability. Because variations in the intensity of the geomagnetic field are global in extent, it will be possible to correlate North Atlantic sediment cores with any other record containing a signal of dipole paleointensity variations. Furthermore, the intensity of the magnetic field modulates cosmic ray flux, making it possible to correlate paleointensity records in marine sediment cores with changes in cosmogenic nuclide production in polar ice cores.

Cores obtained from the Eirik Drift off southeast Greenland during Expedition 303 permitted the development of an offset drilling strategy for Expedition 306 to sample the entire Pliocene sedimentary section on the Eirik drift using only the advanced piston coring (APC) system. However, because of weather delays, Expedition 306 missed the opportunity to pursue this drilling strategy and, hence, to document the drift architecture and climate history since the onset of Eirik Drift deposition. At Site U1302 on Orphan Knoll, a coarse-grained debris flow was encountered near the Brunhes/Matuyama boundary (~790 kyr), which caused the cessation of APC penetration and abandonment of the hole. Unfortunately, the same debris flow was also encountered at Site U1303, and similarly preventing the recovery of the Matuyama Chron (~0.79–2.6 Ma).

Expedition 310 – Tahiti sea level

IODP Expedition 310 sampled the reef terraces around Tahiti, French Polynesia. The primary objectives of Expedition 310 were to establish the history of sea level rise since the end of the last glacial period (i.e., last deglacial period) in a tectonically stable location within the western Pacific, and to define sea-surface temperature variations for the region over the period 20,000–10,000 calendar years B.P. Secondary objectives included the impact of sea level changes on reef growth and geometry. The reef succession from the last deglacial period consist of successive reef terraces seaward of the living barrier reef, was cored and a total of 37 boreholes at 22 sites were completed in water depths ranging from 41.65 to 117.54 m, and with generally excellent core recovery. Successful borehole logging operations in ten boreholes at seven sites provided continuous geophysical information about the drilled strata. Post-cruise studies are likely to produce important results in the following areas:

1) Most if not all of the postglacial succession from the last glacial maximum (LGM) to the present day was recovered. High-quality coral samples suitable for dating and investigations of sea level change are expected to record the detailed course of postglacial sea level rise at in this central Pacific location for the period 18 to10 ka.

2) Slab-sampling of massive coral colonies for paleoclimate studies are expected to define sea surface temperature variations for the region over the period 18 to 10 ka.

3) Cores were from holes in various water depths and situated along three transects, which will constrain the broad temporal and spacial development of the Tahiti reef in response to sea level change.

4) The investigation of the 200 m of cores retrieved from the older Pleistocene carbonate sequences will provide fragmentary sea-level and reef growth information for time windows concerning several isotopic stages.

5) The geo-microbiology pilot study of living bio-films bearing carbonate precipitates that were sampled in situ within cavities, underpins a new field of research regarding the development of microbial communities on modern reef slope environments.

Based on the abstracts and presentations given at the Second Post-Cruise meeting held in Tahiti (November 14 to 16, 2007), the review panel believes that major results will follow in the near future.

3. Achievements

Here we summarize the IODP achievements made so far according to three major IODP research initiatives or targets. These are: (1) Extreme Climates, (2) Rapid Climate Change, and (3) Internal and External Climate Forcing and Sea-level Changes. A brief outlook to already scheduled, but not yet implemented seven IODP expeditions is presented in subsequent section 4.

3.1 Extreme (warm) Climates

Background

One initiative of the IODP ISP is centered around Extreme Climate that, in the ISP wording, is mainly concerned with extreme warm climates in the Late Cretaceous to early Cenozoic. Here, however, we have adopted a broader view of Extreme Climate including the extreme cold climatic intervals such as recent glacial periods and relatively warm periods such as the Pliocene and particularly warm interglacials (e.g. marine isotope stages 31, 11 and 5e). In other words, our evaluation spans the spectrum from absolute extremes to relative extremes and switching between such extremes at various time scales and thus includes overlap with the theme of rapid climate change.

ODP combined with oceanographic modeling has allowed the community to successfully explore a number of other warm and extreme climates. Perhaps the most extreme example of warmth over the past 200 Myr is the Cretaceous. Marked by pervasive organic carbon deposition, extensive and perhaps even ocean-wide anoxia (OAE events), and a high atmospheric carbon dioxide concentration than modern, the Cretaceous intervals have been recovered in many ODP cores, and have revealed aspects of ocean dynamics not previously known from outcrop-based studies.

ODP also contributed truly groundbreaking work on the PETM, a brief period around ~55 Ma of extreme warmth, possibly caused by an unusually rapid increase in atmospheric greenhouse gases (GHG) and generating a truly remarkable climatic spike. The PETM is generally characterized by: (1) a dramatic warming of high-latitude surface water and deep water by ~5-7°C), (2) a remarkable decrease in the $^{13}C/^{12}C$ ratio ($\delta^{13}C$ anomaly of -3 ‰) of global carbon reservoirs, (3) severe dissolution of deep-sea carbonate, (4) the extinction of 35-50 % of cosmopolitan deep sea benthic foraminifera, (5) the appearance of three species of short-ranging planktic foraminifera, (6) a widespread increase in kaolinite (interpreted to herald increased weathering under a warm, wet climate). One interpretation of the PETM is that it resulted from the release of huge amounts of methane hydrate from the seabed (Dickens et al., 1995; Kennett and Stott, 1991) that subsequently was rapidly oxidized to carbon dioxide. Other interpretations suggest sudden release of methane related to large-scale intrusion of magma into hydrocarbon rich basins (Storey et al., 2007). In both of these interpretations, the culprit is a greenhouse gas that was introduced exceedingly rapid to the atmosphere, much in the same sense as the current anthropogenic release of CO_2 and methane.

An additional important aspect of the PETM is the effect of widespread ocean acidification that occurred at that time. Increasing the amount of carbon dioxide dissolved in the ocean lowers the pH and decreases the availability of carbonate ions and lowers the saturation state of the major shell-forming carbonate minerals. Currently the issue of ocean acidification attains much attention because of possible future undersaturation of aragonite in the Antarctic Ocean by the end of this century. The study at PETM may therefore contribute towards an understanding of this future ocean acidification problem.

IODP Achievements

The most prominent achievement by IODP within the theme of extreme climate is the discovery by Expedition 302 of the potentially very strong impact of the PETM into the high Arctic (Moran et al., 2006). Indications are that SST during maximum warmth here were as high as 23°C (Brinkhuis et al., 2006). The finding of this extraordinarily high level is at odds with current climate models and, if confirmed, suggests the existence of very low temperature gradients between low and high latitudes as well as unknown mechanisms of pole-ward heat transfer. Thus, these IODP discoveries regarding the PETM within the Arctic not only contributed scientifically important observations on the global extent and intensity of the PETM, but also generated a large public impact. A number of scientific papers in the journal *Nature* received probably the highest media attention that scientific ocean drilling ever have received.

Expedition 302 retrieved sediment cores spanning from a warm 'greenhouse world' in the late Paleocene and Eocene and into the present cold 'icehouse world'. IRD in the cores is suggested to be present as early as the latest Eocene (~ 46 Ma; St. John, 2008) indicating that at least seasonal sea ice was periodically present at that time. However, due to a stratigraphic hiatus (~44-18 Ma) within the Expedition 302 cores, it is not possible to monitor from these the actual transition of Earth's climate into the late Cenozoic ice-house world. A marked change in the source region of IRD indicates that a more permanent ice cover over the Arctic Ocean was established around 14 Ma (Darby, 2008).

3.2 Rapid Climate Changes

Background

In the IODP Initial Science Plan, "Rapid Climate Change" was identified as an initiative under the theme of "Environmental Change, Processes and Effects". Earth's climate system has undergone large, abrupt jumps repeatedly in the geologic past, especially during the last glacial period when regional temperature in the North Atlantic may have changed by as much as 8° to 16°C. One IODP drilling strategy is to recover an array of sites with high sediment accumulation rates to provide multi-proxy records that can be used to investigate the origin and tele-connections to past abrupt changes in climate under a variety of different boundary conditions and climate states, and during periods of large and rapid changes in climate forcing such as superposition of Milankovitch cycles.

IODP Achievements

During Phase I, IODP has made substantial progress in obtaining materials for the study of rapid climate change. Drilling of sediment drift deposits in the North Atlantic on Exp. 303/306 recovered successions with high sedimentation rates (7-17 cm kyr^{-1}), and are providing critical information on changing surface water hydrography, ice sheet-ocean interaction, and deep-sea circulation on millennial time scales. Likewise, the recovery of massive corals in Tahiti on Exp. 310 provides the material needed for reconstructing past sea-surface temperatures at seasonal resolution for selected time periods between 18 and 10 kyr and studying the rate of deglacial sea level rise. These latter findings are reported in section 3.3.

The North Atlantic Ocean is one of the most climatically sensitive regions on Earth because the ocean-atmosphere-cryosphere system is prone to mode jumps thought to be triggered by changes in freshwater delivery to the source areas of deepwater formation (Broecker and Denton, 1989). Ice and marine sediment cores indicate that the North Atlantic region was marked by rapid fluctuations in air and sea temperatures during the last glacial period. Some of the abrupt changes were accompanied by massive discharge and melting of ice bergs as evidenced by layers of IRD that are depleted in planktic foraminifers and characterized by low oxygen isotopic values indicative of reduced sea-surface salinities. Studies of deep-sea sediment successions indicate that high-frequency climate variability was also prevalent before this period, but such studies have been hampered by the availability of long continuous cores with high sedimentation rates.

The leading hypothesis to explain abrupt climate change in the North Atlantic during the last glaciation involves changes in the strength of thermohaline circulation (for review, see Alley, 2007). Results of ODP Leg 162 have shown that high variability in the climate system has been common over at least the last 1.3 Myr (Raymo et al., 1998). McManus et al. (1999) and Schulz et al., (1999) proposed a link between the amount of continental ice volume and regional and global climate instability. Whenever ice-sheet size, as monitored by benthic oxygen isotopes, surpasses a critical threshold (i.e., $\delta^{18}O>3.5$ per mil or approximately 45-m sea-level equivalent), the amplitude and frequency of variability in ice-rafting and sea-surface temperature proxies increase. The proposed causal mechanism is that when northern hemisphere ice sheets become sufficiently large, they become more prone to instability thereby enhancing production of icebergs and melt water, which diminishes rates of meridional overturning circulation. When ice volume exceeds a critical 'threshold', the climate system becomes more prone to abrupt jumps and variability in the suborbital band increases.

Drilling locations for IODP Expeditions 303 and 306 were chosen to recover long, continuous records of millennial-scale environmental variability from the IRD belt of the North Atlantic (Channell et al., 2006). The sites are distributed along an E-W transect within the so-called Ruddiman IRD belt between 40 and 55°N in the Atlantic Ocean (Ruddiman, 1977). This region contains layers rich in IRD derived from melted icebergs that were produced during massive discharges of ice from the Hudson Straits region of North America (Broecker et al., 1992). Indeed, prominent Heinrich events and detrital carbonate layers deposited during the last glacial period are readily identifiable in density, magnetic susceptibility, and scanning XRF records (Fig. 3) from the new IODP cores. Similar variability in these parameters is observed prior to the last glacial cycle and these records demonstrate the potential of using continuous core logging and scanning XRF proxies to extend the study of these events well beyond the last glacial cycle.

Three of the sites drilled by Exp. 303/306 (Sites 1308, 1312 and 1313) constitute re-occupation of sites drilled during DSDP Leg 94 (Sites 609, 608, and 607). These sites have played a prominent role in some of the most important discoveries in paleoceanography during the last 20 years, but many of the Leg 96 sites were not completely recovered or have been intensely sampled, thereby depleting most of the available core material. In addition, new analytical techniques (core logging, digital imaging, and XRF scanning) now permit rapid, non-destructive determination of changes in physical properties and elemental composition. This technology is especially advantageous for generating long time series records at a resolution that is impractical and/or cost prohibitive using traditional methods.

IODP 303/306 was successful in recovering sediments containing long, continuous records of millennial-scale environmental variability from the North Atlantic that can be used to test the 'threshold hypothesis' (McManus et al., 1999; Schulz et al., 1999). The successions will be important for studying past abrupt changes in North Atlantic climate beyond the last glacial cycle as Earth's orbital configuration, atmospheric pCO_2, and ice volume changed during the Pleistocene. This will lead to new insight into the causal mechanism(s) of abrupt climate change including the interactions among the ocean-cryosphere (e.g. Heinrich events), surface water hydrography (e.g. salinity, sea-ice), and deep-water circulation.

Some of the climatic questions posed by IODP Exp. 303/306 include: (1) When did 'Heinrich events' first appear in the sedimentary record of the North Atlantic? (2) Are they restricted to the '100 kyr world' when ice volume increased substantially? (3) How has millennial-scale variability evolved during the Pleistocene as orbital and glacial boundary conditions changed? (4) Is millennial-scale climate variability related to an ice volume threshold as proposed by McManus et al. (1999)? It is already evident from the preliminary data collected that the cores recovered by IODP 303/306 will yield answers to these questions. For example, the first Heinrich Event at Site U1308 occurred at 650 ka in MIS 16 associated with the end of the Middle Pleistocene Transition (Hodell et al., 2007). Heinrich Events appear to be restricted the 100-kyr world at Site U1308, but results from more proximal (U1302/03) and northern sites (U1304) are needed to confirm this observation. A record of hematite-stained grains (HSG) and Icelandic volcanic glass at Site U1308 suggests that significant differences existed in millennial climate variability between the last and penultimate glaciations (MIS 6) (Obrochta and Crowley, 2007). Enhanced millennial scale variability in siliciclastic supply and deep hydrography has been documented at Site U1314 during ice growth phases when global benthic $\delta^{18}O$ is within a threshold range of ~3.51 to 4.01 ‰ (uncorrected; Gruetzner et al., 2007). In contrast, peak glacial and interglacial intervals reveal low variance in the sub-Milankovitch frequency band. Furthermore, a tight coupling between IRD proxies and benthic $\delta^{13}C$ variation at Site 1308 throughout the Pleistocene (Hodell et al., 2007), supporting a strong link between iceberg discharge and weakening of AMOC.

Abrupt climate events observed in the North Atlantic have been associated with changes in various paleoclimatic records throughout the world, although the phasing, cause, and mechanism of the teleconnections remain uncertain. Improved methods of temporal and stratigraphic correlation are required to correlate millennial-scale events over long distances. In this regard, sediments recovered by Expedition 303/306 are yielding an improved stratigraphic framework for the Pleistocene derived by combining oxygen isotope and relative geomagnetic paleointensity (Channell et al., 2006). Such a framework will be important for regional correlation, and for linking the new records to other marine sediment, lake, and polar ice cores to evaluate the global impact of millennial-scale climate change

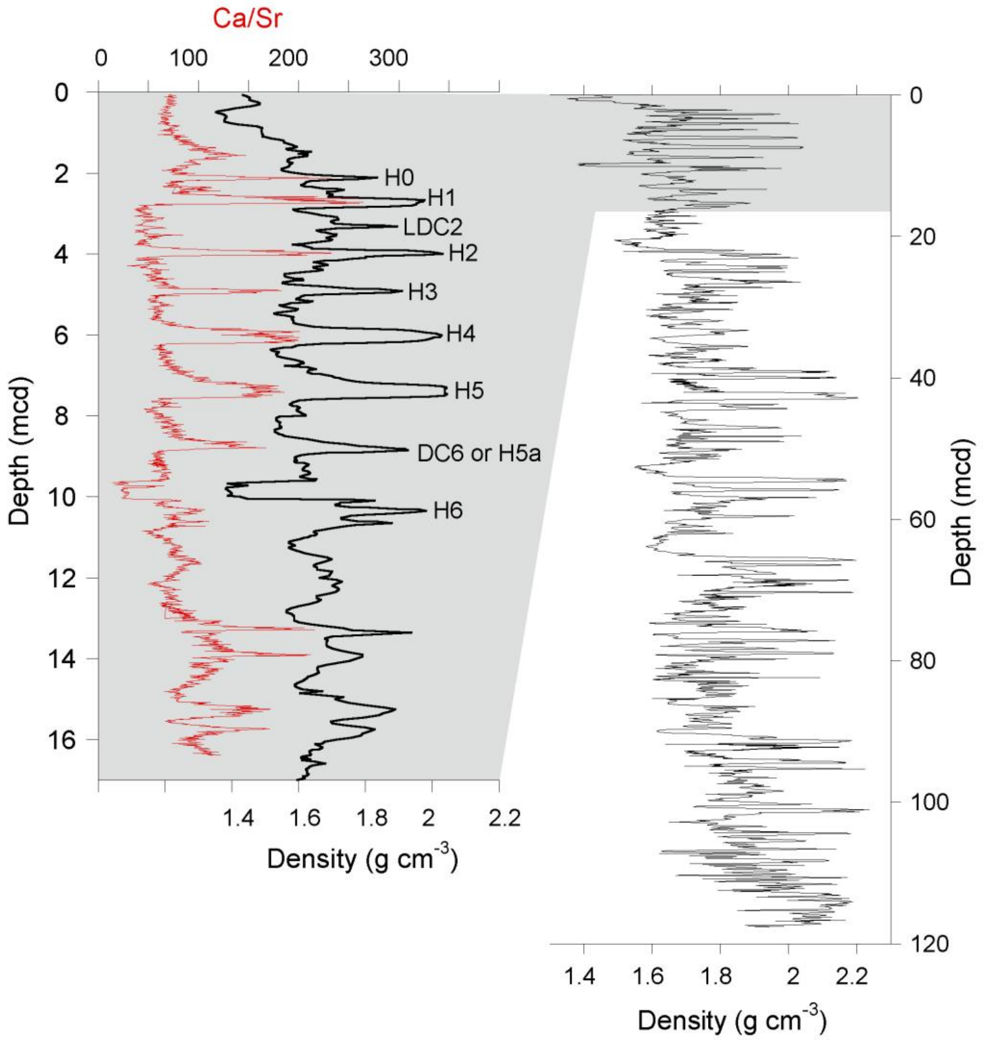

Figure 3. (left) Site U1302/1303 GRA density (black) and Ca/Sr (red) for the top 17 mcd showing the prominent Heinrich (H) and detrital carbonate (DC) events. (right) Density record for the entire spliced section to 120 mcd showing evidence for Heinrich and DC-like events during older glacial periods (Romero and Hodell, 2007).

3.3 Internal and External Forcing and Sea-level Changes

Background

Examples of external forcing of Earth's climate listed by the ISP include Milankovitch cycles in solar insolation and extraterrestrial impacts. Changes in solar insolation are linked to ice sheet growth and decay and ice sheet dynamics, which in turn can affect climate and ocean circulation in a complex set of feedback mechanisms including rapid changes in sea-level. For internal forcing of climate and sea-level change the ISP noted listed tectonics (mountain uplift, oceanic gateways, paleogeography, seafloor spreading rates and ridge lengths affecting ocean volume and global sea-level), and formation of large igneous provinces (LIPS). In addition biogeochemical cycles and the carbon cycling between atmosphere, hydrosphere and lithosphere provides important feedback mechanisms to clime change. Obviously, the biosphere itself plays an important role in shaping the carbon cycle in addition to the physical processes involved in the internal and external forcing mechanisms. As pointed out in the ISP, changes in sea-level can have both internal as well as external origins. And can both result from and contribute to climate change. Together, interactions of external and internal forcing combine to produce the observed climate record.

IODP Achievements: External Forcing

Orbital Changes – Milankovitch changes in insolation provide a well-known forcing mechanism that can be determined independently of the geological record. This in principle allows evaluation of the response of the climate system to Milankovitch forcing under different boundary conditions (e.g. changes in continental configuration and gateways; varying levels of greenhouse gases in the atmosphere and glacial/non-glacial states). Over the past 800 kyr the links among Milankovitch forcing, atmospheric CO_2, the global carbon cycle, and the response of the climate system are confounded by complex feedback and amplification mechanisms associated with large ice sheets, the large-scale ocean and atmospheric circulation (including the monsoons), and carbon/carbonate burial. It is for example becoming increasingly clear that ice sheet dynamics and rapid discharge of large volumes of ice into the oceans through iceberg formation potentially can create rapid changes in ocean circulation and climate (McManus et al., 1999) and thus perhaps act as an amplifier of the external forcing by orbital changes.

The northern North Atlantic sedimentary record is especially sensitive to climate changes related to Milankovitch-paced glacial cycles and changes in freshwater delivery to deep-water source regions. Expeditions 303 and 306 have provided material to address climate variations at Milankovitch, millennial, and centennial-to-decadal timescales as recorded in surface-water hydrography, deep-water circulation, and ocean-cryosphere interactions (e.g. iceberg shedding). Paleoclimatic reconstructions from these data will provide high-resolution records covering the last glacial cycles that will help to resolve whether millennial-scale climate variability is restricted to glacials or occurs also during interglacials. These data are of crucial importance to test competing hypotheses regarding the origin of climate change at millennial timescales (including the existence of thresholds) that are currently being developed for the last glacial cycle. These IODP cores are also expected to provide the first continuous paleomagnetic intensity records covering at least the past 800 kyr with multicentennial-to-millennial scale resolution. By underpinning global stratigraphic correlations of unprecedented accuracy, these new North Atlantic data have the potential to become cornerstones in future stratigraphy and provide essential links between ice-core stratigraphy and marine stratigraphy. Overall, IODP, in concert with earlier DSDP and ODP drilling, has made significant progress in generating data that can constrain external forcing of climate related to Milankovitch cycles in solar radiation, ice sheet dynamics and associated changes in ocean circulation.

Impacts – The ISP also considered extraterrestrial impacts as a possible external forcing of climate and biotic change. Impacts affect climate and, in addition provide craters within the continents with thick stratigraphic records of climate change in the space evacuated by the impactor. Impact study is a potential area of collaboration with ICDP that has drilled craters at Lake Bosumtwi, Chesapeake Bay, Chicxulub, and with drilling planned for Lake El'gygytgyn. Data from these ICDP studies will form very valuable complements to the marine records obtained by ocean drilling. IODP, however, has not so far addressed the specific role of impacts on climate. There is, however, a joint ICDP-IODP proposal to study the Chicxulub impacts crater that would address the effects of impacts on global climate (including the role of sulfates derived from sediment) by examining in detail the impact crater mechanism, volumes and nature of material ejected into the atmosphere.

IODP Achievements: Internal Forcing

Tectonics – IODP is still in the planning stages for expeditions that will evaluate the relationship between mountain uplift and climate (e.g. Asian Monsoon). The Bering Sea expedition will address critical gateway connections between the Arctic and the Pacific. Expedition 303/306 may provide some information on possible recent and subtle changes in the gateway effect of the Greenland-Iceland-Scotland Ridge.

LIPS – An area of the ISP theme environmental changes, processes and effects, that may not be addressed by drilling in Phases 1 and 2 is the interaction of Large Igneous Provinces, climate and biosphere/carbon-cycle. However, an IODP sponsored workshop (July 2007) addressed this issue and will recommend drilling strategies for this topic.

IODP Achievements: Sea-level

Future sea-level rise is one of the consequences of global warming that will have serious societal consequences. Yet the sensitivity and synchronism in response of the Greenland and Antarctica ice sheets to global warming is poorly understood, and is often cited as preventing more precise estimates of future sea-level rise due to global warming. The history of and maximum rates of the late Pleistocene to Holocene sea-level rises during warm interglacials may therefore provide the best indications of to future sea-level rise, but are not well constrained. In particular the pre-Holocene interglacials, which might offer very useful insights, are poorly constrained.

Corals growing near sea level in tropical reef ecosystems represent biological dip sticks that contain a detailed and high-resolution history of rates and magnitudes of sea level change. IODP drilling offshore Tahiti during Exp 310 was successful in recovering corals during the post-glacial period (estimated 16-8 kyr). The cored reef successions appear to be continuous through the 16 to 8 ka interval, and thereby questioning previously proposed widespread reef drowning events caused by exceedingly rapid global sea-level rise (e.g. the rise of 20 m in less than 1 kyr recorded in Barbados during MWP-1A; Fairbanks, 1989). Thirty meters of coral heads recovered from this interval should allow oxygen isotopic and Sr/Ca analysis of the corals that will yield seasonal records of past temperature change for selected time periods during the last deglaciation (~16 and 8 kyr), a time of rapid global warming. Temperature reconstructions on sub-seasonal scale together with climate modeling experiments can offer insights into ENSO variations during this time, what mechanisms lead to ice sheet disintegration and consequent sea-level rise following the last glacial period, and the effects of melting ice sheets on ocean circulation.

The materials recovered will be used to address questions such as: How rapidly did sea-level rise during the last deglaciation? Did Antarctic and Northern Hemisphere ice sheets act in concert, and what were the relative contributions of Antarctic and Northern Hemisphere ice sheets to sea-level rise during MWP-1A (14.1 to 13.9 ka; Fig. 4)?

One exciting outcome of the Tahiti coring is that preliminary results suggest a similar rise as recorded by the Barbados cores during MWP-1A, this potentially implies synchronous bipolar deglaciation. Resolving this long-standing conundrum regarding the origin of the deglacial MWP will have implications for our understanding of the ice-sheet configuration during the last glacial cycle. This, in turn, may help predicting future behavior of the ice sheet during significant and extended global warming.

In summary, application by IODP of a mission specific platform fitted for shallow water reef drilling for the first time ever recovered continuous and detailed records of sea-level change during the Holocene deglaciation. Records of changes in surface water temperature at annual scale resolution are also expected.

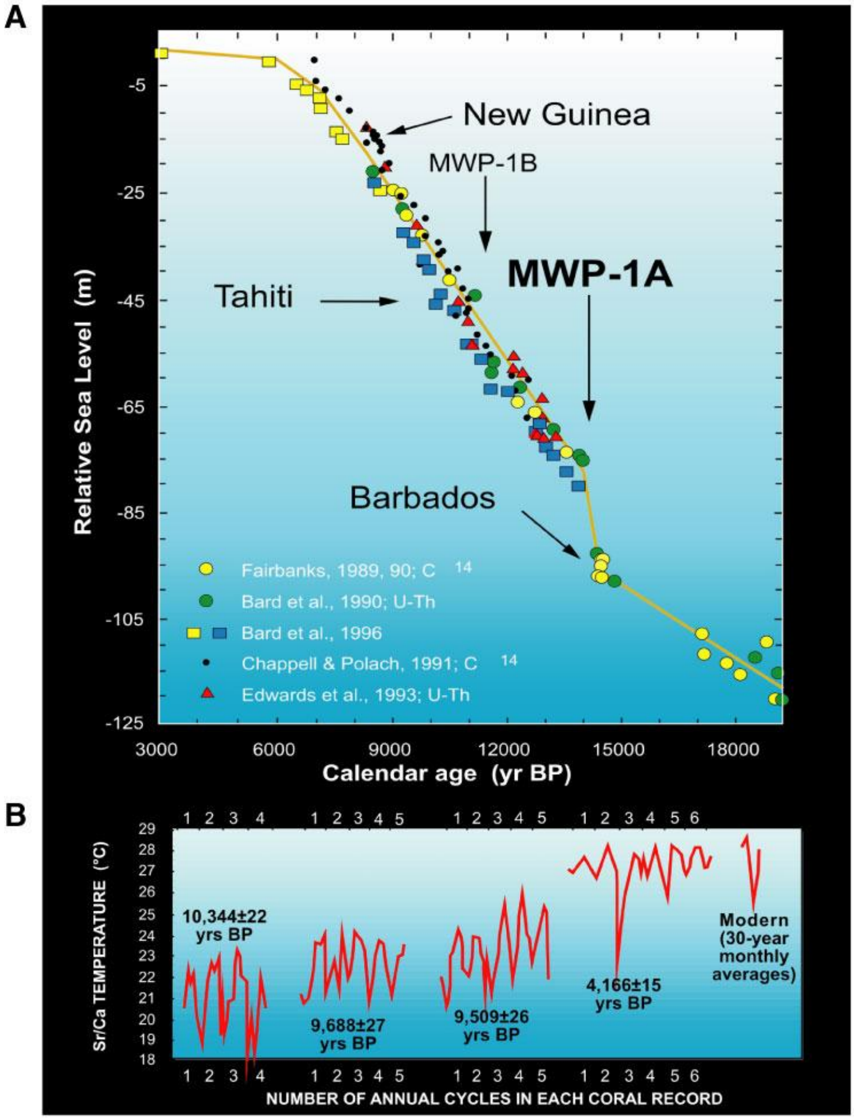

Figure 4. Sea-level history reconstructed for long drill cores from Tahiti (squares), Barbados (circles), and New Guinea (triangles) (from Bard et al., 1996). B. Reconstructed sea-surface temperatures for various time windows on corals from Vanuatu (Beck et al., 1997). MWP = melt-water pulse. (Expedition 310 Scientists, 2007).

4. Planned Drilling Activities

A total of 6 planned IODP expeditions (Fig. 1) within the broader field of climate variability will address the themes of extreme climate, rapid climate oscillations, ice sheet history and sea-level change. The aims and potential contributions of these expeditions to understand natural variability in climate and the underlying mechanisms are briefly outlined below. These expeditions are planned for the period 2008−2009.

Pacific Equatorial Age Transect

An important constraint on our understanding of Cenozoic-scale climate change is our current lack of high-resolution records from the equatorial ocean. Such records would allow us to more fully characterize ocean circulation and productivity during the extreme warm interval of the Eocene, would provide insight into the Earth system response to Milankovitch forcing at a time without permanent ice sheets and during the development of the cryosphere from the Oligocene to present. The equatorial Pacific drilling project is planned to recover equatorial sediments back to the early Eocene with a first (our of two) expeditions to start in 2008.

The objectives of the equatorial Pacific expedition are: (1) resolving questions of how and why paleoproductivity of the equatorial Pacific changed over time, (2) providing material to validate and extend the astronomical calibration of the geological time scale for the Cenozoic, (3) determining sea-surface and bottom-water temperature and nutrient profiles and gradients, (4) providing information about the detailed nature of calcium carbonate dissolution and changes of the CCD, (5) enhancing our understanding of bio- and magnetostratigraphic datum levels at the equator, (6) providing information about rapid biological evolution and turnover during times of climatic stress, and (7) improving our knowledge about the reorganization of water masses as a function of depth and time.

The equatorial Pacific project is likely to contribute the IODP themes of extreme (warm) climate, the role and external (Milankovitch) forcing of climate, carbon cycling and to extend the astronomically tuned geological time scale further back in the Paleogene.

Wilkes Land

Wilkes Land Drilling will explore: (1) the onset of Cenozoic glaciation in Antarctica, (2) Neogene glacial dynamics and history, and (3) the history of the East Antarctic Ice Sheet during the Miocene. This expedition has the potential to counterpart previous ODP efforts and current efforts by the ANDRILL program (Harwood et al., 2006) and SHALDRIL program (Wellner et al., 2005) to constrain glacial history in Antarctica and will thus be helpful in understanding the links between gateway influences, ocean circulation, and atmospheric GHG content on Earth’s Southern cryosphere and on global heat transport. Challenges to success for the expedition continue to be the difficulties of age control in these target sediments and sediment recovery in successions with varying till lithology. A strategy of sampling both proximal and distal deposits (with less abundant IRD component) based on extensive seismic mapping may prove successful in alleviating this potential sampling problem.

Bering/Okhotsk Sea

The Bering/Okhotsk Sea drilling project aims to constrain: (1) variation in surface water conditions, paleoproductivity, and sea-ice coverage during Pliocene-Pleistocene period at millennial – to Milankovitch-scale resolution, (2) the history of past production of the Pacific intermediate and/or deep water masses within these marginal seas, and its link to surface water processes, (3) the interactions between the oceanographic conditions and adjacent continental climatic conditions, (4) the linkages between processes in the Bering sea (e.g. variations in deep water formation, or water mass exchange through gateways) and changes in the pelagic Pacific.

The Bering/Okhotsk Sea is a key area in the North Pacific for global climatic change, because Bering/Okhotsk Seas are thought to be the source area of North Pacific Intermediate Water (NPIW), which would have an important role in changing ocean environments by controlling variations of bottom water ventilation. Since these seas are surrounded by East Asian and north American landmasses, drill cores are expected to contain continental climate records. Furthermore, the drilling in these seas will bridge the gap between the North Atlantic, the Arctic and the northern North Pacific, and expect to supplement the results from Arctic Ocean and North Atlantic expeditions.

Presently the Bering/Okhotsk sea drilling is planned for 2 phases. Bering Sea phase (Fig. 1) is currently scheduled for 2008. A second expedition to easternmost Bering Sea and Sea of Okhotsk is pending scheduling and permitting. When completed as originally planned, drilling in the Bering/Okhotsk Seas will provide the ‘Pacific’ high-latitude complement to North Atlantic and Arctic Drilling, critical information about water movement history through the Bering Strait gateway and the role that the North Pacific might have played in bottom water production in the past.

Planned Expeditions Addressing Sea-level Change

A fairly substantial effort is planned for the years 2008-2009 to study sea-level change in both siliciclastic and carbonate (reef) environments. Two expeditions are planned to drill the New Jersey shallow shelf and Canterbury Basin, New Zealand, respectively. Both expeditions will constrain the longer-term sea-level variations as recorded in these siliciclastic basins, focusing on the Miocene time interval. The New Jersey shallow shelf expedition, completing a series of ODP and ICDP drilling dating back to 1993, will address early Miocene eustatic amplitudes through 1-D and 2-D backstripping (e.g. Kominz et al., 1998; Kominz and Pekar, 2001). These results will complement estimates of global sea-level change derived from ICDP drilling onshore New Jersey, and allow estimates of the full amplitude of sea-level change. The Canterbury Basin will provide a Miocene comparison to the sea-level records from the New Jersey margin. In addition, it will provide the response of sedimentation to sea-level variations, changes in geostrophic currents, and the tectonic development of the Alpine thrust in New Zealand and associated changes in sedimentological regime.

An expedition to drill into the Great Barrier Reef is planned for implementation in 2009. If conducted, the planned coring will complement result from the IODP Tahiti coring covering the last deglaciation and may extend estimates of the sea-level curve back in time as far as 1 Myr, albeit at lower temporal resolution than obtained for the last deglacial by the Exp. 310 Tahiti operations.

5. Links to Other Programs

Various organizations are engaged in obtaining pre-historic records of climate change at various time scales through scientific drilling on land, sea, and ice. As such, IODP can gain from cooperation and interaction with the terrestrial drilling communities, and with marine shallow coring and sampling initiatives such as IMAGES (http://www.images-pages.org/). For example, IODP, ICDP, and the various projects engaged in ice coring (GISP, GRIP, EPICA, WAIS, etc.) have many synergistic goals and common approaches to studying Earth history through scientific drilling. More than any other topic, the study of abrupt climate change is a prime example of a common initiative shared among all three communities and of utmost societal importance.

Two regional marine coring programs focusing on Antarctica, ANDRILL (http://www.andrill.org/) and SHALDRIL (http://shaldril.rice.edu/) in particular focus on the climatic development of this continent, with in part very similar objectives as IODP. However, coordination of scientific priorities between IODP and these programs is not formalized, though IODP is assisting ANDRILL with review of the site characterization of planned drill sites.

ICDP has made major strides in obtaining long, continuous sediment cores from lakes for terrestrial paleoclimate research (Harms and Emmermann, 2007; Bringham-Grette et al., 2007). Recent drilling campaigns have focused on lowland tropical lakes in Africa (Bosumtwi, Malawi) and Central America (Peten Itza). Marine sediment cores adjacent to the continents also contain high-fidelity records of past changes in terrestrial climate and vegetation. Opportunities therefore exist for joint IODP/ICDP projects that involve parallel drilling of complementary lake and marine cores with coordinated research objectives to integrate results from the terrestrial and marine records. The IODP/ICDP communities also share many of the same needs for instrumentation, drilling technology, database development, and core curation. Co-operative efforts between the programs are currently taking place through informal liaison activity between the two programs and the successful partnership between IODP and ICDP in the joint publication of the journal Scientific Drilling. This has enhanced communication between the scientific constituencies behind the two programs (Emmermann and Talwani, 2005). Another example is joint sponsorship of the New Jersey margin drilling transect and two ICDP/IODP workshops planning for drilling the Chicxulub impact crater and sea-level changes. Likewise, a topical symposia on North Atlantic climate variability (Bremen, 2007) successfully drew attendees from both drilling programs. However, we see additional opportunities for closer cooperation between IODP and ICDP from the early stage of project planning through data dissemination in pursuit of the common goal of climate change research.

The ice core community has made exciting finds in the field of paleoclimatology over the last 20 years. For example, the discovery of rapid climatic changes in Greenland ice cores during the last glaciation launched the study of millennial- and sub-millennial scale climate variability in marine records. The long records of changing temperature and atmospheric composition (e.g. CO_2 and CH_4) from Antarctica ice cores have challenged us to identify the causes of these changes and the role of the carbon cycle in forcing glacial-to-interglacial climate change. In many respects, the polar ice core records have become an unofficial ‘type-sections’ for climate change over the past 800 kyr, to which marine and terrestrial paleoclimate records are compared (Alley, 2003). Although ice cores are extremely powerful paleoclimatic archives, understanding the Earth's climate system requires a coupled ocean-atmosphere and global approach where the ice core data are integrated with marine sediment core records from an array of geographically distributed sample locations (e.g. Lisiecki and Raymo, 2005). In addition, the importance of the long EPICA-DOME C ice core (Jouzel et al, 2007) would be greatly enhanced if the atmospheric changes observed could be placed in the context of variability in surface (SST, productivity) and deep-water (circulation, nutrient content) conditions throughout the oceans. Ice cores are also limited in terms of the time period covered. The oldest ice in Greenland is limited to last climate cycle (~123 kyr; NGRIP, 2004), whereas the oldest ice core from Antarctica is presently ~800 kyr (Jouzel et al., 2007). Identifying marine sediment analogs to the polar ice cores would strengthen ties between IODP and the ice core community, advance a coupled ocean-atmosphere approach to climate change research, and by use of long marine sediment cores, in particular in the Antarctic region, extend such studies into the early Pleistocene and beyond during times of different boundary conditions.

6. Paleoceanographic Data and Climate Modeling

Over the past years climate modeling has become increasingly important in the area of paleoclimatic research. Specifically, physically based climate models provide a valuable tool to assess conceptual models of past climate changes derived from paleoclimatic data. On the other hand, data-based reconstructions of past climate variations provide critical test grounds for climate models that are usually tuned to capture present-day climate. Accordingly, combining data-based reconstructions and paleoclimate modeling is now recognized as an important track to fully comprehend past climate dynamics (Fig. 5).

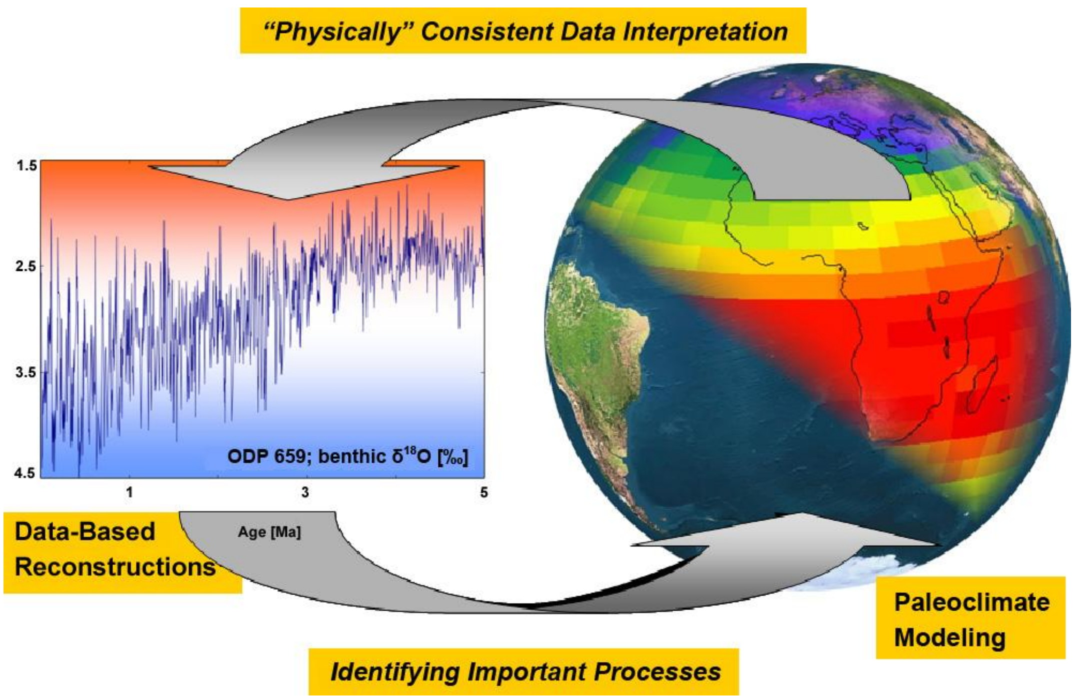

Figure 5. Combining data-based reconstructions and paleoclimate modeling to decipher past climate dynamics. (data from Tiedemann et al., 1994).

Specific benefits that can result from the joint utilization of paleoceanographic reconstructions and paleoclimate modeling include a means for formulating and testing hypothesis, e.g. by quantifying the response of the climate system to forcings. Moreover, climate models provide a comprehensive framework for exploring couplings and feedbacks between the various components of the climate system. This type of analysis is of special relevance for detecting thresholds in the climate system. Finally, climate models offer a link between past climate changes and projections of future climate, which is assessed by the same type of models.

Key areas in which IODP can be expected to contribute essential data to the assessment of future climate change on timescales of societal relevance include: understanding climate dynamics under high atmospheric CO_2 concentrations, quantifying ice volume and sea level during previous interglacials, evaluating the response time of ice sheets to radiative forcing, gauging rates of sea-level change, quantifying natural climate variability at decadal-to-millennial timescales, and, detecting thresholds in the climate system. Key findings from ODP have now been incorporated into the Fourth Assessment Report of the IPCC (2007). The combination of IODP-based paleoceanographic reconstructions and climate modeling thus shows potential to disentangling climate dynamics on timescales of societal relevance.

To raise the awareness of IODP findings beyond the paleoceanographic community further, it appears advantageous to involve modelers or physical oceanographers already during the planning stage of an IODP project. This approach would help to choose sites most sensitive to specific climate changes and to ensure that site selection is based on up-to-date oceanographic information. Moreover, it would strengthen the existing links between paleoceanographers, climate modelers and physical oceanographers.

A fruitful collaboration between climate modelers and paleoceanographers depends also on the availability of proxy and model data. IODP should strongly encourage scientists working on IODP samples to make the data available through a World Data Center in a format suitable for the modeling community. Likewise, important model output from paleoclimatic modeling experiments should be made available in a format that is easily accessible by paleoceanographers.

7. Technology Issues and Sampling Policy

IODP successfully employed new drilling concepts in order to access the least known ocean on Earth − The Arctic Ocean (Expedition 302). IODP also successfully has adopted new technology (diamond coring) to recover continuous core from reef environments (Expedition 310, Tahiti). Previous attempts by ODP to recover this kind of lithology were highly flawed by very low recovery. This pretty much prevented scientific ocean drilling from exploring these potentially very rewarding environments in pursuit of high resolution climate and ocean studies. However, alternating successions of hard (e.g. chert) and soft layers, diatom mats, unconsolidated sand, and core disturbance during RCB drilling remain as challenges to continuous and undisturbed core recovery from environments of potentially high interest to paleoclimate research, but located in water depths in excess of viable diamond coring technology.

Continuous XRF scanning has proven a very promising laboratory tool in high resolution stratigraphic work, which could be applied retroactively to ODP cores. However, a fundamental problem is that a large number of samples are taken and causes significant problems with core integrity and record continuity. New technological developments like the XRF thus already have encountered limitation in their application to archived core material because of the practice of samples occurring even on archival halves of the cores. The core XRF instrument functions ideally on a clean unsampled core surface, and the non-destructive nature of XRF is consistent with the proper archival of core material. While intense sampling of the cores for discrete sample analysis well may be justified in a number of cases, it must be realized that high-resolution stratigraphy in the field of paleoceanography has become dependent on the preservation of full half cores, or at least U-Channels from these. For these reasons, we recommend that the program reviews its sampling and coring policies.

8. Conclusions and Recommendations

8.1 General Comments

The research fields of paleoceanography and paleoclimate remain a strong asset of IODP involving a broad field of scientists and recent drilling results have reached world news headlines. In its first drilling phase (2004−2005), IODP has successfully continued and developed high-resolution paleoceanographic and paleoclimatic studies that were established as a new field of research by the DSDP and ODP. The IODP provides advances over ODP with the additions of MSP's, allowing exploration of high latitude and shallow water environments not previously accessible for coring by scientific ocean drilling. In addition, IODP has provided improved core recovery (reef environments in particular), developed more complete composite sections by application of multiple hole strategies, and applied high-resolution stratigraphic tools such as continuous XRF core scanning and paleomagnetic intensity variations. IODP drilling is beginning to realize the potential for integration with other related communities such as ICDP lake drilling, ice coring, and climate modelers. Given that research in this field occupied only four dedicated expeditions out of the 12 IODP expeditions conducted in the years 2004−2005, the achievements made are truly impressive.

These IODP achievements should form a strong basis for continued, if not increased, deliberations by IODP in this field of research with obvious tie to global warming research. Thus, during IODP, the IPCC has acknowledged scientific ocean drilling data to provide important (paleo)climate data of importance for modeling of future global warming and its effect on the Earth and its habitability. This provides IODP with an opportunity to strategically link its (paleo)climate research to other components of the multidisciplinary climate research. However, with the unfortunately very limited resources of drilling time available within IODP, the program may have to make some hard choices of program priority regarding its research within the fields of paleoceanography and paleoclimate. Ties to and coordination with related drilling programs such as ICDP (e.g. lake drilling), shallow coring programs (e.g. IMAGES), ice coring and modeling community are recommended. Experiment design may in specific cases benefit from an integrated approach with related programs at an early stage (e.g. ICDP).

8.2 Extreme (Warm) Climates

The most spectacular achievement by IODP was the successful recovery of the first deep cores from the Arctic Ocean. This achievement made world news headlines in relation to both operations, and later on, also in relation to some of its findings, in particular the potentially excessive impact of the PETM on the high Arctic climate and environment around 55 Ma. However, because of a large stratigraphic hiatus in the cored section and some problems with core recovery, the Arctic expedition was less successful in documenting the transition from the warm and non-glacial early Paleogene into full glacial conditions in the high Arctic within the late Neogene. Possible future drilling efforts must be planned to maximize the chance of complete sampling of this critical section at an appropriate location. Other priorities for future Arctic drilling should include a cross-polar view of late Neogene climate and ocean dynamics with linkage to Bering Sea and Sea of Okhotsk drilling, and confirmation of the presence of regionally extreme warm SST across the Arctic basin during the PETM. This may require drilling both near the Expedition 302 site, and within the Canadian Basin in order to achieve a representative data set for the entire Arctic ocean.

The rapid and extreme nature of the PETM potentially may make it an appealing analog to potential consequence of continued anthropogenic increase in atmospheric GHG. IODP should carefully consider its continued role in the study of this and more recent 'relative extreme' warm periods (e.g. the Early Miocene, mid-Pliocene, and warm Pleistocene 'stages' 31, 11, 5e and others), which may constrain mechanisms and 'tipping' points for non-linear behavior of climate warming. Also, while a return the Arctic would be a major program undertaking, it is in the medium to long-term required in order to complement and verify the results by Expedition 302.

8.3 Rapid Change

IODP has made truly important strides in recovering materials from the North Atlantic and developing methodology and stratigraphy for studying rapid climate change. However, additional records of high temporal resolution are needed from other regions that are less well-studied. A fuller understanding of the causes and consequence of rapid climate change will require the recovery of a global array of high-resolution cores spanning different time intervals. Annual-to-decadal resolution records, such as those provided by laminated marine sediments (e.g. Cariaco Basin, Santa Barbara Basin), are also needed to produce ultra-high-resolution, multi-proxy records of past environmental conditions. Multiple proxy data are essential for correlating records from geographically distributed locations because different proxies record different components of the climate system that potentially vary on different time and space scales (e.g. Shackleton, 2000).

Finally, marine sediment records, from the planning stage to use in modeling, should be better integrated with lake and ice core records. In an editorial, Alley (2003) thus recommends that the paleoceanographic community should adopt an ice-core approach and "generate a few internationally coordinated, multiply replicated, multi-parameter, high-resolution type sections of oceanic change". These deep-sea sections of sufficiently high sedimentation rates to resolve millennial scale climate variability will permit even more detailed comparisons with Greenland and Antarctic ice cores. Some candidates for oceanic type sections of this resolution already exist (e.g. Lisiecki and Raymo, 2005), including sites recently drilled by Expeditions 303/306, but additional targets should be identified for future drilling by IODP especially in the Southern Ocean and equatorial regions.

The field of rapid climate change and high-resolution paleoceanographic records is obviously a successful and important component of IODP with high potential for links to other programs and communities. In addition, it has profound societal relevance. It is therefore of concern that the scheduled (or near scheduled) IODP expeditions only include limited activity in this area. This might significantly reduce the prospects for IODP to further generate timely and significant results in this area before the current phase of the program ends in 2013. However, more proposals may rise to the level of possible scheduling, and an IODP workshop on high-resolution climate studies, is scheduled for 2008 and may generate increased proposal pressure in this area. IODP is recommended to carefully monitor its position and progress made in the field of rapid climate change.

8.4 Driving Forces and Sea-level Change

Already conducted and planned IODP expeditions will strongly contribute to better understanding of the 'external driving forces' of climate change represented by the changed in solar insolation (i.e., Milankovitch cycles), in particular the recent ice-house world. But past IODP activities did not target internal driving forces such as mountain uplift or formation of LIPS. However, the planned expedition to the Bering Sea will address an important oceanic gateway between the Arctic and the Pacific oceans. IODP Monsoon Detailed Planning Group (2008) recommends a coordinated drilling strategy for studies of internal (i.e., mountain uplift) forcing and external (Milankovitch cycles) forcing of the Asian monsoon. An IODP workshop (July, 2007) on LIPS may generate increased proposal pressure in an area that so far have seen neither completion, nor scheduling of any IODP drilling activity.

With planned and completed expeditions, IODP will also make major inroads into deciphering sea-level change (Expeditions 310 Tahiti and Great barrier Reef, Expedition 313 New Jersey Shallow Shelf, and Canterbury Basin) and its effect on stratigraphic architecture in siliciclastic settings. A topic of increasingly societal importance is to document the maximum rate of sea-level change during recent deglaciations, as well as during past warm intervals such as the middle Pliocene and the extreme interglaciations of the Pleistocene (MIS 5, 11 and 31 for instance). IODP is recommended to carefully review its options to contribute to the latter highly societal relevant subject.

8.5 Carbon Cycle and Climate Change

Over the course of the Neogene, paleoceanographic reconstructions based on ODP samples have revealed major climate transitions that seem to have occurred without corresponding changes in atmospheric CO_2 concentration on orbital-to-tectonic timescales (Pagani et al., 2005). These findings, if borne out by future studies, preclude a simple correlation between atmospheric CO_2 content and mean climate at long timescales and pose a major challenge for our understanding of the link between the carbon cycle and climate. IODP is in a unique position to address this question, but has not made progress in this area during its first years, nor are there any concerted effort scheduled or in the works. The climate-research community would benefit greatly if IODP would stimulate a fresh look at the carbon cycle on orbital-to-tectonic timescales, e.g. by exploring potential links between shallow and deep biosphere. As an outcome, one could expect a better representation of the global carbon cycle, including past atmospheric CO_2 levels, in long-term climate models. It might also offer an opportunity to link the developing field of deep biosphere studies to climate research.

8.6 Data and Sample Availability

Expanding the use of ocean drilling samples and data into new and cross-disciplinary studies may require IODP to review the visibility of its cores, samples and data to users outside its current community. In principle, there currently is no hindrance for any scientists to access IODP (and legacy ODP/DSDP) samples and data. However, format and interoperability of data (including post expedition data) may be optimized to provide for easier 'discovery' and use by the broader community. Sampling and coring policy may also have to be adjusted to new methodologies and expanded user numbers. If pristine full archive core halves cannot be preserved, at least preservation of minimum totally unsampled U-channels of (archive) core halves in IODP core repositories must be secured. Multiple coring at legacy sites should also be considered including revisits to older sites for which continuous cores do not exists.

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Acronyms

ACEX – Arctic Coring Expedition
AMOC – Atlantic Meridional Overturning Circulation
ANDRILL – ANtarctic DRILLing Project
APC – Advanced Piston Corer
CCD – Carbonate Compensation Depth
DSDP – Deep-Sea Drilling Project
ENSO – El Niño-Southern Ocean Oscillation
EPICA – European Project for Ice Coring in Antarctica
GHG – atmospheric Greenhouse Gases
GISP – Greenland Ice Sheet Project
GRA – Gamma Ray Attenuation
GRIP – Greenland Ice Core Project
HSG – Hematite-Stained Grains
ICDP – International Continental Scientific Drilling Program
IMAGES – The International Marine Past Global Change Study
IODP – Integrated Ocean Drilling Program
IODP-MI – Integrated Ocean Drilling Program Management International
IPCC – Intergovernmental Panel on Climate Change
IRD – Ice Rafted Debris
ISP – Initial Science Plan
LGM – Last Glacial Maximum
LIPS – Large Igneous Provinces
mbsf – meters below sea floor
MIS – Marine Isotope Stages
MSP – Mission Specific Platform
MWP – Melt-Water Pulse
NADW – North Atlantic Deep Water
ODP – Ocean Drilling Program
PETM – Paleocene-Eocene Thermal Maximum
RCB – Rotary Core Barrel
SHALDRIL – Shallow Drilling Along the Antarctic Continental Margin
SST – Sea Surface Temperatures
WAIS –West Antarctic Ice Sheet
XRF – X-Ray Fluorescence