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Introduction

Cretaceous and Paleogene marine deposits provide accessible archives to document Earth system processes during partly to entirely deglaciated states. Although investigations of these ancient times have traditionally fallen into the category of basic academic research, recent results obtained through ocean drilling suggest that important and societally relevant issues can be addressed with Cretaceous and Paleogene sequences. These issues include the stability of tropical sea surface temperatures, the relationship between biodiversity and climate, and the global effects of carbon cycle perturbations. Ironically, the best examples of rapid, wholesale extinctions linked to climate change or massive input of carbon come from Paleogene and Cretaceous records rather than those from more recent times.

The Cretaceous and Paleogene portion of the geological record is punctuated by several transient intervals of extreme climate. These brief (10^3 - 10^6 yr) time intervals are characterized by profound fossil turnovers and major upheavals of the global carbon cycle. The combined rate and magnitude of observed biogeochemical change during these events is unparalleled in the Neogene except at present-day.

Certain key intervals of the Cretaceous and Paleogene are marked by rapid climate change and massive input of carbon. These intervals are the Late Paleocene Thermal Maximum (LPTM) and Oceanic Anoxic Events (OAEs) in the early Aptian and at the Cenomanian/Turonian Boundary. Although the PPG acknowledges the existence of other fascinating time intervals of the Cretaceous and Paleogene (e.g., Aptian/Albian boundary interval, the late Albian, the mid-Maastrichtian, the Cretaceous/Tertiary Boundary, the Eocene/Oligocene Boundary), the chosen two time intervals are particularly significant to current Earth science objectives because focused research has the potential to considerably improve our understanding of the general dynamics of the Earth during rapid perturbation of the carbon cycle. The group stresses that the LPTM and OAEs were also marked by prominent (but selective) turnovers in major fossil groups. A thorough knowledge of Earth system processes during these extreme climate intervals would significantly contribute to our understanding of biological evolution.

Several important pieces of information are required to understand basic Earth processes and biological evolution during extreme climate intervals of the Cretaceous and Paleogene. This information includes critical components of the ocean system such as the mode and direction of thermohaline circulation, the amount and composition of carbon, oxygen and other dissolved species in various ocean reservoirs, and the temperature gradients of surface and deep water. Most importantly, the PPG recognizes the need for quantification of climate proxies before, during and after extreme climate intervals. We cannot address important global-scale issues on the thousand-year time scale without continuous, high-resolution depth transect records at multiple locations. Critical to this endeavor will be the development of an astonomically-tuned Cretaceous and Paleogene time scale.

The inaugural meeting of the Extreme Climates of the Cretaceous and Paleogene Program Planning Group (PPG) was held on 16-17 September 1998. Dr. Ellen Thomas, the ESSEP liaison, introduced the role of the PPG, and urged the group to be as practical as possible by (1) defining outstanding scientific objectives relevant to the PPG, and (2) selecting ocean drilling strategies and targets that can meet these objectives.

In the following report, we detail why knowledge of the LPTM and OAEs is important to Earth science, and highlight a general interest in studying biological turnovers during the Paleogene and Cretaceous. We then discuss how available ocean drilling and scientific approaches can be used to understand the selected extreme climate events. Of particular interest to the ESSEP, the PPG identifies the Walvis Ridge and Newfoundland Margin as two locations where well-designed ODP drilling legs could significantly improve our knowledge of extreme climates of the Paleocene and Cretaceous.

Late Paleocene Thermal Maximum (LPTM)

Our society is concerned with the fate of fossil fuel carbon which we are presently adding to the atmosphere of the global carbon cycle at a rate of 5 x 10e14 mol C/yr during an interglacial time interval that already is warm. Although we have a considerable understanding of how the global carbon cycle operates, we have limited knowledge on how a rapid and massive input of fossil fuel will perturb the global carbon cycle and related systems. Studies of the Neogene geological record provide boundary conditions for the global carbon cycle. However, these records provide no analog for our current fossil fuel forcing function, or massive carbon input during a time interval that was already warm.

A brief time interval at (or near) the Palaeocene/Eocene Boundary (ca. 55 Ma) is now known to have been characterized by a rapid 4 to 8 °C increase in deep ocean, high-latitude and continental temperatures as well as major turnovers in terrestrial and marine flora, fauna and microbiota (e.g., Kennett and Stott, 1991; Zachos et al., 1993; Thomas and Shackleton, 1996; Fricke et al., 1998). This time interval has been coined the "Late Palaeocene Thermal Maximum" or LPTM (Zachos et al., 1993). The LPTM is notable for a prominent negative carbon isotope excursion of at least -2.5‰. This $\delta^{13}C$ excursion has been documented in planktic and benthic foraminifera in sediment of all oceans, in fossil tooth enamel and carbonate concretions in terrestrial sequences of North America, and in terrestrial organic carbon in sediment from Europe and New Zealand (e.g., Kennett and Stott, 1991; Koch et al., 1995; Kaiho et al., 1996; Thomas and Shackleton, 1996; Bralower et al., 1997; Schmitz et al., 1997). On the basis of estimated sedimentation rates, the onset of the $\delta^{13}C$ excursion occurred within 10,000 yrs, and the entire excursion likely spanned about 200,000 yrs (Kennett and Stott, 1991; Bralower et al., 1997; Schmitz et al., 1997). The timing, magnitude and global nature of the $\delta^{13}C$ excursion may be unique in the Phanerozoic record.

The isotope excursion across the LPTM is especially intriguing from a mass balance perspective because it cannot be explained unless an immense quantity of CO_2 greatly enriched in ^{12}C was rapidly added to the ocean or atmosphere (Dickens et al., 1995; Thomas and Shackleton, 1996). This inference is consistent with pronounced dissolution of carbonate in deep sea sediment deposited during the LPTM (Thomas and Shackleton, 1996; Dickens et al., 1997; Bralower et al., 1997; Thomas, 1998).

One plausible explanation for the observed LPTM $\delta^{13}C$ excursion involves massive release of CH_4 from gas hydrates in the ocean (Dickens et al., 1995, 1997; Kaiho et al., 1996). This hypothesis suggests that a change in ocean circulation caused significant warming of intermediate to deep ocean water during the LPTM (Kennett and Stott, 1991). This warming resulted in steepened sediment geotherms on continental margins and thermal dissociation (melting) of gas hydrate. Methane released from gas hydrate and underlying free gas zones then escaped to the ocean or atmosphere where it was oxidized to CO_2. Simple models have demonstrated that release and oxidation of between 1 and 2 x 10e18 g of CH_4 with a $\delta^{13}C$ of -60‰ into the present-day exogenic carbon cycle over 10,000 yrs results in geochemical perturbations similar to those observed across the LPTM (Dickens et al., 1997). No other reasonable explanation for the observed $\delta^{13}C$ excursion has been offered.

The importance of the observed carbon cycle perturbation at the LPTM is that it strongly suggests release of reduced carbon to the ocean and atmosphere at rates approaching those of present-day anthropogenic inputs of fossil fuel at a time of profound climatic, biological, and geochemical change. The LPTM is to be the only known analog in the geological record for understanding how the global carbon cycle and other systems relate to a rapid and massive input of fossil fuel.

Outstanding issues surrounding the LPTM include the following:

* what was the cause of carbon input? Was it CH_4 from the seafloor and did it lead or lag changes in the chemistry and temperature of the ocean and atmosphere?

* what was the cause of the apparently rapid thermohaline reversal and did it precede carbon input?

* where was the carbon added? Was carbon added first to the atmosphere or ocean?

* what was the rate of carbon input and did it vary over time?

* what was the nature of climate variability across latitude before, during, and after the LPTM?

* how did the carbon input and temperature increase affect biological systems?

* did tropical SST increase during the LPTM? If so, to what extent?

Oceanic Anoxic Events

Understanding the causes and effects of major disturbances in the steady-state carbon cycle is a primary objective currently facing the ocean sciences. Investigations of mid-Cretaceous Ocean Anoxic Events (OAEs) have become focal points in this endeavor because they represent major perturbations of the ocean system defined by massive deposition of organic matter in marine environments (Schlanger and Jenkyns, 1976; Jenkyns, 1980; de Graciansky et al., 1984; Arthur et al., 1990). Although similar events are known from earlier time intervals of the Mesozoic and Palaeozoic, they cannot be studied extensively because deep-ocean records are unavailable. OAEs did not occur during the Tertiary.

There were arguably between two and five OAEs during the mid-Cretaceous. Each of these OAEs was different in geographic extent, but all record rapid changes in the carbon cycle, and all were associated with major changes in marine biota (following section). Two of these events, the late early Aptian Selli Event (=OAE1a; ~120 Ma) and the Cenomanian/Turonian Boundary Bonarelli Event (=OAE2; ~93.5 Ma) are particularly prominent, with sedimentary records in all ocean basins (Arthur et al., 1990; Bralower et al., 1994). Both events were likely associated with major steps in climate evolution since burial of excess organic carbon, by drawing down CO_2, apparently initiated global temperature decline from relative maxima (Jenkyns, in press).

Recent high-resolution work indicates that OAE1a (“Selli event”) was characterized by a complex sequence of apparently global biogeochemical variations. An interval of rapid radiation in calcareous nannoplankton was followed by a marked negative $\delta^{13}C$ excursion and loss of nannoconids (Erba, 1994). This negative $\delta^{13}C$ precursor has now been verified in Alpine sections of southern and northern Tethys (Weissert and Lini, 1991; Menegatti et al., 1998), in southern England (Gröcke et al., in press) and at Resolution Guyot in the Pacific (Jenkyns, 1995). In most of these localities this negative $\delta^{13}C$ excursion is superseded by an abrupt positive $\delta^{13}C$ excursion. Black shales of the Selli Event occur exactly at the stratigraphic level where $\delta^{13}C$ values rapidly increase from relatively low to relatively high values.

The series of events surrounding OAE1a has been linked to the Ontong Java-Pacific "superplume" event, whereby a profound increase in submarine volcanism may have forced global warming and increased marine productivity (Larson, 1991; Erba,1994; Follmi et al., 1994; Menegatti et al., 1998). Such a scenario is consistent with an observed decrease in the $^{87}Sr/^{86}Sr$ ratio of seawater (Ingram et al., 1994; Jones et al., 1994; Bralower et al., 1997). One hypothesis (Bralower et al., 1994) also relates the distinct negative $\delta^{13}C$ perturbation to input of mantle-derived CO_2 associated with submarine volcanism.

Sediments rich in marine organic matter of Cenomanian-Turonian Boundary age have been recovered from all ocean basins (Arthur et al., 1990). As evidenced by widespread laminated sediment and a variety of geochemical indices (e.g., Dickens and Owen, 1995; Sinninghe Damsté and Köster, 1998), the response of the carbon cycle during OAE2 was somehow related to dysoxic to euxinic conditions in the water column, although the exact cause and dimensions of O_2-deficiency remain unclear and controversial.

The substantial positive $\delta^{13}C$ excursion of sea water at the time of OAE2 (Scholle and Arthur, 1980; Schlanger et al., 1987; Jenkyns et al., 1994) has also been attributed to increased productivity and carbon burial. Here, however, it is unclear whether heightened productivity was stimulated by changes in circulation, water-mass sources (Arthur et al., 1987, 1990; Leckie, 1989), or submarine volcanism (Sinton and Duncan, 1997; Kerr, 1998). A negative $\delta^{13}C$ excursion precursor has not yet been identified for OAE2 (Jenkyns et al., 1994). However, plateau volcanism at 93-90 Ma is recorded in the Pacific and Caribbean, and there is a decrease in the $^{87}Sr/^{86}Sr$ ratio of seawater (Ingram et al., 1994; Jones et al., 1994; Bralower et al., 1997).

Major issues surrounding extreme climate and the carbon cycle during
OAEs include the following:

* what were the specific triggers leading to abrupt perturbations of the carbon cycle? Was it submarine volcanism? Was it elevated nutrient concentrations? Were the two phenomena related?

* what was the ultimate cause of O_2 deficiency? Was it enhanced productivity, reduced circulation, or input of alternative oxidizing agents?

* what was the vertical extent of O_2 deficiency?

* were all OAEs linked to greenhouse warming?

* what was the nature of climate variability across latitude before, during, and after OAEs?

* how did the carbon input and oceanographic changes affect biological systems?

* how did oceanic temperature structures change during different OAEs?

Biotic Response During Extreme Climates

The modern pressure on marine and terrestrial ecosystems highlights our ignorance of the long-term consequences of rapid habitat changes on biotic evolution and the maintainence of biological diversity. Although we know a considerable amount about the causes of the modern crisis, it is far less clear how resilient the biosphere is to major climate events or how changes in nutrient cycling and thermal gradients influence the evolutionary process on long timescales. Just as the LPTM and OAEs provide analogs for modern rapid climatological changes, these events also offer the opportunity for analyzing the biological response to global perturbations.

The Paleogene to Cretaceous "extreme greenhouse" period was a time characterized by major marine and terrestrial biotic turnovers many of which fundamentally restructured biotic communities and established the 'modern' fauna and flora. Most of these events seem to be linked to major changes in climate and oceanography, and the mid-Cretaceous OAEs and LPTM are excellent examples. Yet nearly all these events remain poorly understood, in large measure because previous deep sea drilling targeted relatively condensed sections or failed to recover the entire sedimentary column. We also are just beginning to establish direct correlations between marine and terrestrial sections which are invaluable for deducing the role of the atmosphere and climate in these turnover events.

The Early Aptian OAE1a (Selli-Event) was a major turnover event for calcareous nannoplankton, radiolaria, planktonic foraminifera, and benthic foraminifera (Erba, 1996; Erbacher and Thurow, 1997; Kaiho 1998; Coccioni et al., 1992). The OAE2 (Bonarelli event) was even more pronounced, with major extinctions in the above groups, ammonites, bivalves and even angiosperms (Boulter et al., 1998; Kuhnt and Wiedmann, 1995; O´Dogherty,1994; Erbacher & Thurow, 1997; Coccioni et al., 1995; Jarvis et al., 1988; Kaiho, 1998; Kaiho and Hasegawa,1994; Leckie, 1989).

Current models for biotic turnover during the mid-Cretaceous OAEs largely invoke O_2 deficiency and eutrophication of the oceans. For example, an increase in oceanic productivity during OAE1a (Weissert et al., 1998; Grötsch et al., 1998) may have resulted in expanded oxygen-minimum zones (OMZs) in several areas (Caron & Homewood, 1983; Erbacher et al., 1996) that, in conjunction with rapid eutrophication, could have caused extinctions and subsequent radiations in a variety of marine groups (Norris and Wilson, 1998). Leckie (1989) also stressed the importance of upper water column thermal gradients in influencing the nature of productivity and plankton evolution, and how these gradients may have changed with rising sea level and different modes of water mass production. However, these theories require testing with faunal, biogeographic, and isotopic data that establish the sequence of turnover in groups with different susceptibility to low oxygen conditions and nutrient cycling at orbital resolution. Correlations between marine and terrestrial ecosystems are particularly important as a means of determining whether a process like 'anoxia' is a primary cause in extinction or merely a secondary result of some larger process.

The LPTM is associated with a suite of biological events that include extinction of about 50-55% of deep sea cosmopolitan benthic foraminifera (Thomas, 1998) and a major immigration event of mammals to North America and Europe (Koch et al., 1995). New mammals suddenly appearing in the fossil record include the first recorded ancestors of primates. Although it is unclear where the new mammals came from, it is likely that this major mammal dispersion event involved the opening of high-latitude gateways and elevated temperatures both of which may also have played important roles in the benthic foraminifer extinction (Meng and McKenna, 1998).

Notably, the warming at the LPTM is not associated with major turnovers in planktic foraminifera and nannoplankton (Kelly et al., 1996). These groups both experience more significant speciation and extinction several 100 ky after the (^{13}C excursion (Pardo et al. 1997; Aubry 1998). Indeed, the turnover in marine planktonic groups is approximately coeval with an interval of elevated extinction in mammal faunas from Wyoming and a jump in land plant diversity from the same area (Koch et al., 1992, Maas et al. 1995, Wing et al. 1995; Wing, 1998). Floral assemblages from the Bighorn Basin provide evidence for an approximately 5^{o}C drop in temperature associated with the biotic changes immediately after the LPTM. The delay in biotic turnover suggests that the LPTM was part of a larger series of climatological events that had major biological effects, such as the ramp-up to the early Eocene Warm Period. Hence, it is critical to analyze not only the LPTM event itself, but also its larger context in the late Paleocene-early Eocene. It has also been speculated that there may be at least one additional late Paleocene to early Eocene carbon isotope event (Stott et al., 1996). Unfortunately, it has been extraordinarily difficult to construct a complete and unambiguous chronology of detailed events surrounding the Paleocene/Eocene Boundary.

Oustanding issues relevant to biological change during extreme climates include the following:

* are observed turnover events abrupt or do they occur over an extended period?

* how taxon-specific are the turnovers and are particular ecological groups more profoundly affected than others?

* are turnover events associated with just the onset of warm periods and OAEs or do the terminations of these events also produce turnovers? That is, is the magnitude of forcing more important than its direction?

* how do turnover patterns compare between the marine and terrestrial realms?

* was provincialism substantially different than at present-day?

Milankovitch “Reference Sections”

Until recently, paleoceanographic studies of warm intervals of the Paleogene and Cretaceous carried the label “low resolution”. While this description derived correctly from the typically low-resolution sampling intensity of most existing biostratigraphic, stable isotopic, or geochemical studies of these periods, it also reflected the view that warmer worlds were inherently less climatically variable than the late Neogene, and that in any case that stratigraphers would never resolve time in older geological sections to better than perhaps 0.5 Myr intervals. Better sampling has brought to light brief, extreme excursions in the ocean/atmosphere system such as the Paleocene/Eocene event (LPTM), that challenge the “low resolution” paradigm. Recent recognition of another class of high frequency events, semi-periodic features in sedimentation and/or biotic composition that show statistical patterns and periods characteristic of variations in the earth’s orbital elements (eccentricity, obliquity, and precession) open up the possibility of studying geologically warm periods at resolutions similar to those achieved in the Pleistocene (Park and Herbert, 1987; Herbert and D’Hondt, 1990; Gale, 1989; Huang et al., 1992).

Targetting orbital reference sections, with the requirements of continuous sedimentation, complete core recovery, and optimal integration of other stratigraphic tools (i.e. magnetostratigraphy, biostratigraphy, and chemostratigraphy), promises to advance our quantitative understanding of past climates in two major ways. First, we can view climatic variance in the “Milankovitch” band as a unique experiment in climate sensitivity. The forcing functions (variations in sunlight received at the top of the earth’s atmosphere as a function of season and latitude) that have driven the Plio-Pleistocene ice ages have continued into the remote past with very nearly their recent values. While celestial mechanics cannot provide complete solutions to the earth’s orbit much beyond 10 Myr, the statistical behavior of the orbital terms can be deduced (Berger et al., 1992). The earth itself has evolved as part of this oscillating pattern of insolation anomalies, and, by working in the Milankovitch band, we have the chance to detect which aspects of climate sensitivity, and which geographic regions, maintain responses to orbital forcing, so many of which are well documented for the Pleistocene epoch.

Orbital cyclicity, as it does for Pleistocene paleoclimatology, also provides the best practical method for measuring elapsed time. It thus has the potential to greatly increase the temporal resolution of global correlations based on geomagnetic polarity time scales (e.g. Cande and Kent, 1992; 1995; Berggren et al., 1995). For example, the well-known secular trend of increasing geomagnetic reversal frequency from Cretaceous Long Normal polarity interval to the present results in a yardstick that measures time to only 0.5-1 Myr resolution. Determining the duration of events within polarity chrons, and documenting their correlation between sites, relies, in the absence of orbital chronology, on the assumption of constant sediment rate. The ability of properly sampled cyclic sections to measure time in 20, 40, and 100 kyr increments clearly adds to the study of any aspect of warm climates where determing rates is important. One example in which orbital dating has improved the resolution of a geologically important "event" comes from studies of the Cretaceous/Tertiary boundary, where cyclic sequences with reliable magnetostratigraphies and good core recoveries have increased constraints on the shortness of the K/T transition, and documented the slow recovery of the sedimentation and planktonic foraminiferal diversity following the K/T event (Herbert and D'Hondt, 1990; Herbert et al., 1995, D'Hondt et al., 1996). The succesful application of cyclostratigraphic techniques will be critical to our understanding of the LPTM which occurs with a 2.5 M.Y. long polarity chron (C24R) and to the OAEs which generally occur within the 30 M.Y. Cretaceous Long Normal, for example, the Bonarelli (OAE2) at the Cenomanian/Turonian boundary.

Few Paleogene and Cretaceous sections have been sited or cored optimally to record orbital stratigraphies. The existing orbital template is patchy, with good coverage only in the ealiest Paleocene through the Late Cretaceous (early Campanian). The encouraging observation is that so many sections, despite episodic core recovery, suggest a strong orbital influence. Simple, relatively easily measured of lithological variance (measuring % CaCO3, % Corg, etc.) or indirect lithological proxies (reflectance spectroscopy or magnetic susceptibility) work well to produce time series with clear “Milankovitch” features. Down-hole logs tied to analysis of cores may well play a role in the future. Few high-resolution stable isotopic time series of Paleogene and Cretaceous age exist, but these may show patterns paced by orbital cycles as well. Focused efforts to drill sites with moderate Neogene cover, with a high likelihood of obtaining magnetostratigraphies, which must be the “backbone” of high-resolution studies, and with multiple-hole strategies should result in a near-continuous marine “Milankovitch” template into the middle Mesozoic.

Drilling strategies

Many issues relevant to understanding the LPTM and OAEs can be addressed by the same drilling strategies that are currently and successfully employed for tackling Neogene paleoceanographic objectives. Drilling transects should be conducted at multiple locations where chosen drill sites have three criteria: (1) a wide range of paleodepths, (2) good preservation of primary carbonate,

(3) high sedimentation rates across time intervals of interest, and (4) good potential to preserve a paleomagnetic signal or contain sediments with strong magnetic susceptibility.

Issues of rate and magnitude during OAEs and the LPTM require continuous stratigraphic records. This can only be accomplished by complete core recovery through chosen intervals by taking multiple cores, and logging holes with the formation microscanner (FMS). In relation to this is the need for an astronomically-tuned Paleogene and Cretaceous time-scale. Observed biogeochemical changes during extreme climate intervals of the Cretaceous and Paleogene occur significantly faster than the temporal resolution by conventional stratigraphic approaches. Key issues concerning timing, magnitude, and rate of change during the LPTM and OAEs will have to be pursued with the same rigor applied to Neogene sediment records. Earlier DSDP and ODP legs have provided initial reconnaissance to indicate that astronomical approaches can be extended into Paleogene and mid-Cretaceous sequences.

The reason for the above criteria can be appreciated by considering logical objectives for understanding extreme climate during the LPTM. For example, rapid release of 1 x 10e18 g of CH_4 with a $\delta^{13}C$ of -60‰ into the deep Atlantic Ocean over 10,000 yrs should result in an average annual removal of 4.5 x 10e14 g of dissolved O_2, and substantial dissolution of $CaCO_3$ that would be represented by a burndown of previously deposited carbonate and a major shoaling of the CCD (Dickens et al., 1997). Moreover, such deep ocean carbon input would result in an intriguing temporal offset whereby the $\delta^{13}C$ shift in benthic foraminifera will precede the $\delta^{13}C$ shift in planktonic foraminifera. A series of depth transects in each of the major ocean basins would allow for characterization of the $CaCO_3$ dissolution event as well as quantification of dissolved O_2 and $\delta^{13}C$ of different water masses. Ultimately, in order to model and understand basic biogeochemical perturbations during the LPTM, the Earth science community will need to know the rate, magnitude and relative timing of surface water warming, deep water warming, carbon input to the deep ocean, carbon input to the shallow ocean, carbon input to the atmosphere, O_2 deficiency in the deep ocean, carbonate dissolution on the seafloor, and biological turnovers in the deep ocean, shallow ocean, and on land. Such links can only be addressed by correlating numerous sites from different environments at the 100 to 1000 year time-scale.

A very important consideration is depth of burial of the mid-Cretaceous sections. Expanded mid-Cretaceous sections that haven't been deeply buried are the highest priority targets of OAEs. Areas such as the J-Anomaly Ridge and Newfoundland Ridge in the North Atlantic, Exmouth Plateau and Scott Plateau of the southeast Indian Ocean will provide complementary mid-latitude localities for comparison with the well-preserved tropical records of OAE1b, 1d, and 2 cored on Blake Nose during ODP Leg 171B.

Finally, there may be a connection between the OAEs, generation of oceanic lithosphere, mantle plume activity, sea level and continental weathering (e.g., Larson, 1991; see also Ingram and Richter, 1994; Heller et al., 1996). A key unknown is the rate of sea floor spreading during the Cretaceous Long Normal; due to the lack of diagnostic magnetic anomalies during the Cretaceous Quiet Zone, the rate of lithospheric production can only be estimated as an average over about 30 m.y. of the mid-Cretaceous. At such coarse resolution, it is not possible to determine if there was a global increase in the rate of sea floor spreading that coincided with the pulse of Ontong-Java superplume activity toward the beginning of the Cretaceous Long Normal. This problem can only be addressed by drilling, i.e., direct sampling and dating of ocean floor within the Cretaceous Quiet Zone in different ridge systems. Sediment immediately overlying basement should have been deposited when the ridge was at its shallowest and thus should generally preserve an age-diagnostic calcareous fossil assemblage. The main constraint on any basement site used for this purpose is a known flow-line distance from the end(s) of the Quiet Zone; such sites can be considered holes of opportunity on different legs to build up an inventory of age information on the global ridge system in the mid-Cretaceous. Such opportunities should be sought in conjunction with planning for drilling in the Atlantic Ocean (e.g., Walvis Ridge and Newfoundland Ridge).

Existing proposals in the system

Several current proposals in the system relate to Paleogene and Cretaceous drilling. Depth transects need to be drilled to obtain information on deep water circulation (and thus nutrient cycling). Evidence is needed for rapid changes in ocean chemistry and reversals in deep water circulation that might trigger or accompany these extreme climates. This requires multiple high resolution records from well chosen depth transects. Drilling at Shatsky Rise as proposed by Bralower et al (Shatsky Rise, proposal

534) represents a primary target for a Pacific Cretaceous and Paleogene depth transect. Potential sites have already been identified on both the southern and central Plateau using new multi-channel seismic lines. Other target areas could be proposed sites of deep water formation-around the Tethys, N. Atlantic, and Southern Ocean. Useful would be a transect of cores across the equator. There is one proposal in the system that highlights an equatorial transect (Lyle et al., Paleogene Equatorial Pacific APC Transect, proposal 486).

The Antarctic margin in the eastern Weddell Sea may contain a unique and well-preserved high latitude record of OAE1a and 1b based on coring during ODP Leg 113. A return to the Weddell Sea would be strongly supported by the 'extreme climate' PPG (proposal 503, Weddell Sea). The Scott Plateau is a target area of interest for Neogene palaeoclimatological study, but could also be an interesting drilling target for older warm climate objectives because it features Cretaceous sediments containing well-preserved microfossils of Campanian age outcropping on the sea floor. Therfore, the PPG has recommended that the authors (Opdyke et al., proposal 513, Scott Plateau) of the existing proposal consider rewriting the proposal to include the targeting of a Cretaceous section at one site.

New proposals

The Atlantic was chosen because new proposals would stand a better chance to be drilled in the current Ocean Drilling Phase to 2003. These areas were also promoted in the MESH Report (1997). All PPG members favoured the idea of promoting the following two areas to obtain high resolution records that could be useful for the above mentioned objectives.

Walvis Ridge

The biggest obstacle facing our understanding of the climate of Paleogene, particularly the abrupt transient events such as the LPTM, is the lack of quality high resolution, multi-cored sequences. Most existing sites suffer from poor recovery and drilling disturbance. Many were only single cored, and virtually none were drilled as part of multi-site depth transects.

One of the most promising locations for recovering Paleogene sediments and the LPTM is Walvis Ridge in the south Atlantic. Walvis Ridge was the target of deep sea drilling during DSDP Leg

72. Five single hole sites were drilled as a depth transect along the northern flank of the ridge from 2500 to 4400 m water depth. Sequences of Paleogene pelagic sediments characterized by high sedimentation rates and superb magnetic signatures were recovered at each site. In general, however, recovery was relatively poor at all sites (~50%), especially with the XCB in relatively shallow sediments. Nevertheless, the LPTM was recovered within a clay layer at the deepest hole, Site 527. The carbon isotope and oxygen isotope records based temperature estimates obtained from analysis of benthic foraminifera from this site have provided key points in our understanding of this event (Thomas & Shackleton, 1996). At the shallower sites, the LPTM was lost in the core gaps. With higher resolution seismic stratigraphy, it should be possible to design a transect of 5 to 6 multi-hole sites that will capture the LPTM in sediments from a paleodepth range spanning >2000 m. Such a transect would provide adequate constraints on several key aspects of the LPTM event including the timing and magnitude of the CCD/lysocline shoaling and recovery in the South Atlantic. The shallower sites would provide well preserved planktonic foraminifera for reconstructing changes in surface water conditions (i.e., temperature and chemistry).

New Foundland Ridge

The New Foundland Ridge gives an excellent opportunity to core complete sections that contain information on deep water mass structure. Previous drilling (DSDP 384) found a nearly complete Paleocene and Upper Cretaceous section with well preserved siliceous and calcareous fossils and good magnetic stratigraphy. The Paleogene and Cretaceous sections (which include Eocene oozes and Albian-Aptian shallow water limestones) thicken considerably to the east of DSDP 384 and also preserve a depth transect of over 1500m paleowater depth. New drilling on J-Anomaly Ridge should be able to recover an expanded Paleogene and upper Cretaceous section that records the chemistry and paleoecology of North Atlantic deep water. Previous studies by Corfield and Norris (1996) and Barrera and Savin (1998) based on DSDP 384 have demonstrated that the Cretaceous and early Paleogene deep North Atlantic was filled with very different waters than the rest of the world ocean.

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