General introduction and synopsis

Atmospheric CO_2 concentrations expected for the next centuries have not been equaled since the early Paleogene, approximately 66 to 45 Million years (Ma) ago. The early Paleogene global climate appears to have been substantially warmer than that of present day, likely in response to high greenhouse gas concentrations. For example, large ice sheets were absent during most of this period. Understanding of the impact of such 'greenhouse' conditions on early Paleogene global climate is vital to identify and quantify present and future climate feedbacks related to rising atmospheric carbon concentrations. The research I have carried out focused on a wide range of early Paleogene time intervals, including the late Paleocene, early Eocene and Middle Eocene, late Eocene, and earliest Oligocene (see CV on p. 226). In this thesis, I shall specifically focus on global change that occurred during a brief period of extreme global warming called the Paleocene-Eocene thermal maximum (PETM), approximately 55.5 Ma ago.

Close to the Selandian - Thanetian boundary (~59 Ma), a long-term global warming trend initiated, which culminated in the Early Eocene Climatic Optimum (EECO; 52-50 Ma). During the middle and late Eocene long term cooling occurred, eventually resulting in significant expansion of Antarctic ice sheets during the earliest Oligocene. Although greenhouse gas concentrations are likely to have played an important role, the mechanisms behind these long-term trends are still poorly understood. The PETM, which characterizes the Paleocene-Eocene boundary, is almost certainly associated with increased greenhouse gas concentrations. The warming is evidenced by large oxygen isotope ($\delta^{18}O$) excursions in marine and terrestrial carbonates and increased Mg/Ca ratios in foraminifera. Furthermore, poleward migration of (sub)tropical marine and terrestrial biota characterizes the PETM. Associated with this warming is a negative 2.5-6 ‰ stable carbon isotope ($\delta^{13}C$) excursion (CIE), evidencing the fast injection of ^{12}C-enriched carbon in the form of CO_2 or CH_4 into the global exogenic carbon pool. The apparent conjunction between the carbon input and warming has fuelled the hypothesis that the increased atmospheric CO_2 and/or CH_4 concentrations caused an enhanced greenhouse effect at the PETM, superimposed on the already high greenhouse gas concentrations of the earliest Paleogene. The duration of the negative $\delta^{13}C$ excursion and the subsequent recovery is in the order of 170 kyr.

Although many studies have focussed on the PETM, basic questions on the nature of this event have remained unanswered. First of all, why did the PETM occur when it did and is it unique in Earth's history? Second, to which degree is the input of light carbon that caused the CIE causally related to global change? In deep marine sections, the CIE and the $\delta^{18}O$ excursion occur at the same level, but these sections are relatively condensed and are not suitable for detecting (sub)millennial-scale leads and lags. Many PETM sections from the deep sea show strong dissolution of carbonate related to a shoaling of the lysocline, but the effect of elevated carbon concentrations on ocean carbon chemistry has not been quantified. Moreover, although reasonable estimates for low latitude warming exist, the question remains what the magnitude of warming on a global scale has been? And what effect did this warming have on sea level?, This thesis addresses all of the above questions by detailed multi-proxy analyses of a variety of sites from the deep sea to the shelf and from extreme high to low latitudes.

Among the most important proxies that have been used to detect paleoenvironmental changes reported in this thesis are the organic-walled cysts of dinoflagellates (dinocysts). Dinoflagellates are protists. The different species have a wide range of ecological preference: for instance some are heterotrophic, some are autotrophic, and some are more competitive in warm waters, whereas others thrive better in cold waters. Over the past decades, the ecology of extant species and the paleoecology of extinct taxa (although we only know their cysts) have been mapped increasingly well. Dinocyst assemblages in sediments can, hence, be used to reconstruct the ecology of the waters in which the dinoflagellates lived. By presenting case-studies from around the globe, **Appendix 1** provides a concise state-of-the-art review of our present understanding of the paleoenvironmental significance of dinocysts in the Paleogene (~ 65-25 Ma). Representing long-term as well as transient warming and cooling, this episode holds the key to the understanding of dinocyst paleoecology as well as their potential in reconstructing paleoenvironments. We discuss how dinocysts can be used for the reconstruction of Paleogene sea-surface productivity, temperature, salinity, stratification, and paleo-oxygenation along with their applications in sequence stratigraphy, oceanic circulation, and general water mass reconstructions.

Many data in this thesis are generated on sediment cores that were drilled in the framework of Ocean Drilling Program (ODP) Leg 208 on the Walvis Ridge in the subtropical Southeast Atlantic (2003) and Integrated Ocean Drilling Program (IODP) Expedition 302, or the Arctic Coring Expedition (ACEX) on the Lomonosov Ridge in the Arctic Ocean (2004). These cruises have provided a wealth of new data on the Late Paleocene through Early Eocene and some of these have been included in chapters 1 to 3 of this thesis.

Almost all carbon which was injected into the ocean-atmosphere system near the onset of the PETM should in theory have rapidly dissolved in the ocean as CO_2. As argued in **Chapter 1**, this should have led to higher concentrations of H^+ ions which would almost immediately dissolve biogenic carbonate. Hence, significant shoaling of the lysocline (depth in the ocean at which carbonate particles produced in the surface waters start to dissolve) and the calcite compensation depth (CCD; depth below which all carbonate is dissolved) is to be expected. Furthermore, sequestration of the excess carbon by silicate weathering and organic carbon burial would ultimately lead to the recovery of the lysocline and CCD. ODP

Leg 208 successfully recovered undisturbed PETM successions along a ~2 km paleodepth transect, and the records as presented in this chapter confirm all the above aspects.

During ODP Leg 208, in addition to the PETM, we recovered a ~2 Ma younger clay-rich layer, which was as red as a doll of the Sesamestreet character *Elmo* that had been sitting in the core laboratory on the drillship JOIDES *Resolution*. We, therefore, affectionately named this red horizon after *Elmo*. This layer also reflects carbonate dissolution and exhibits negative $\delta^{13}C$ and $\delta^{18}O$ excursions in biogenic carbonate, implying another brief episode of global warming similar to the PETM but of a smaller magnitude. Detailed comparison with a variety of earlier studies shows that carbonate dissolution and negative $\delta^{13}C$ at this time interval are global in nature, indicating that the *Elmo* horizon represents a phase of global warming that we termed 'the Eocene thermal maximum 2' (ETM2). These results are presented in **Chapter 2**, in which the first preliminary orbital tuning of the interval between the PETM and *Elmo* is included. This tuning suggests that the onsets of both the PETM and *Elmo* correspond to maxima in the 100 and 400 kyr eccentricity cycles, implying an insolation-forced internal trigger for both events.

A previously noted aspect of Late Paleocene and Early Eocene climates is the apparently decreased temperature gradient between tropical and polar regions compared to today. However, firm estimates of absolute surface temperatures >80° N were unavailable due to the lack of cores from the (central) Arctic Ocean. During the ACEX, a latest Paleocene – middle Eocene sediment section was partially recovered that was deposited at ~85° N. In **Chapter 3** we identify the PETM in the ACEX cores based on dinocyst and stable carbon isotope stratigraphies. The results show that the dinocyst *Apectodinium*, a taxon which was restricted to low latitude regions before the PETM but showed significant poleward migration during the PETM (see cover), even invaded the Arctic Ocean. In addition, the records suggest that significant changes occurred in terrestrial vegetation in the Arctic region and that photic zone euxinia and bottom water anoxia developed during the PETM. Application of the organic paleothermometer TEX_{86} suggests that surface ocean temperatures rose from ~18° C to ~24° C at the PETM, followed by a decrease to ~18° C during the recovery. Pre- and post, as well as PETM temperatures are much higher than those predicted with fully coupled paleoclimate model simulations, implying that these models have difficulties to simulate the reduced pole-to-equator temperature gradients that prevailed during this time interval. Hence, important temperature forcing mechanisms that cooled the tropics or warmed the poles were active at that time, which are not implemented in the current generation of climate models. Finally, the magnitude of Arctic warming is similar to that recorded in surface and bottom waters and terrestrial estimates from around the globe including the tropics, implying that no polar amplification occurred during the PETM.

To assess absolute temperature values and the PETM temperature anomaly at mid-latitudes we applied a combination of TEX_{86} and foraminifer $\delta^{18}O$ paleothermometry on a site from the New Jersey shelf, USA. The results are presented in **Chapter 4**. Also at this site the *Apectodinium* acme is recorded. The temperature warming recorded in TEX_{86} is slightly smaller than that implied by the negative foraminifer $\delta^{18}O$ excursion. We attribute the offset between these two proxies to a decrease in sea water $\delta^{18}O$ due to a slight salinity decrease during the PETM.

Despite the many studies that have focused on the PETM, the ultimate question of what caused this event has not been answered. Several - not mutually exclusive - hypotheses have been proposed to explain the CIE and the warming. Although many authors prefer the hypothesis that the dissociation of submarine methane hydrates was at the root of the CIE and part of the warming, problems exist with this, and all other hypotheses proposed to date. A detailed review of the published literature on proposed causes for the PETM is provided in **Chapter 5**. We argue that, although the extensive study on this phase in Earth's history has led to the recognition of a number of constraints, the exact cause of the PETM is not yet determined. This chapter also includes a review of the marine and terrestrial biotic responses and how these responses have been interpreted in terms of paleoecological and climatic change. In addition, the most prominent geochemical characteristics are included, as well as a discussion on the various age models that have been generated for the PETM.

The proxy-records in the above chapters and those published by other authors indicate that tropical and high latitude surface ocean waters, as well as deep ocean waters warmed quasi-uniformly by ~5°C during the PETM. Such a rise in ocean temperatures should lead to significant thermal expansion of ocean water. Furthermore, the presence of small Antarctic ice sheets during the greenhouse conditions of the earliest Cenozoic has been invoked by various studies. In theory, thermal expansion and the melting of such Antarctic ice sheets imply that eustatic sea level rise should have taken place at the PETM. In **Chapter 6** we assess variations in proximity to the coast across the PETM of four continental margins by using dinocyst assemblage changes. Dinocysts consistently show a trend to more distal assemblages starting ~20 kyr before the PETM. This trend is corroborated by sediment size fraction data and the relative amount of terrestrially derived palynomorphs and organic molecules versus those of marine origin. We estimate that the invoked transgression by means of thermal expansion and melting of continental ice could have maximally comprised 10 meters.

The idea that warming occurred simultaneously with the CIE at the PETM derives from the numerous deep sea carbonate $\delta^{18}O$ and $\delta^{13}C$ records, which show negative excursions at the same stratigraphic level. However, deep sea sections are in general relatively condensed and, on top of that, suffered severe carbonate dissolution at the PETM (Chapter 1), leading to extremely low sediment accumulation rates. Neritic sections potentially yield much higher sedimentation rates, particularly across the PETM because the transgression (Chapter 6) resulted in larger accommodation space on the shelves. In **Chapter 7** we present unprecedented high-resolution dinocyst, stable isotope, and sometimes TEX_{86} records across the PETM of the North Sea, the New Jersey shelf and combine these with previously published records from New Zealand. We show that the onset of the global acme of the dinoflagellate *Apectodinium* and subsequent surface-ocean warming as recorded by TEX_{86} preceded the CIE by ~5 kyr and ~3 kyr, respectively. Considering that no evidence of any additional environmental change at the CIE is apparent from our records, the input of ^{12}C-enriched carbon may not have caused significant environmental perturbations. Moreover, these data suggest that the pre-CIE global change somehow triggered the injection of ^{12}C-enriched carbon rather than the other way around. Interestingly, the time scale for thermal destabilization of methane hydrates is in the order of thousands of years, which is exactly in accordance with the time lag we record between warming and the CIE. The cause of pre-CIE warming is unclear, but if it was forced by increased atmospheric carbon concentrations, that carbon must have been in isotopic equilibrium with the latest Paleocene exogenic carbon pool, suggesting the source may have been the ocean.

Summarizing, the results presented in this thesis provide answers to several of the primary questions that were addressed above. Although comprizing a regional signal only, the CCD shoaled for at least 2 km in the southeast Atlantic Ocean, which may require a larger injection of carbon than can be explained by the assumed dissociation of submarine methane hydrate. Based on the *Elmo* horizon and correlation to other sites around the globe, we now know that the PETM was not a unique event but the most severe of multiple 'hyperthermal' events during the late Paleocene and early Eocene. This strongly suggests an endogenic cause for these phases of rapid global warming. The results from the Arctic Ocean and the New Jersey shelf provide a better constraint on the very high temperatures that prevailed globally during the late Paleocene and early Eocene and particularly during the PETM. These results indicate that climate models cannot realistically produce climates, particularly meridinional temperature gradients, during these episodes of enhanced atmospheric greenhouse gas concentrations. Despite of the globally warm temperatures, Antarctic continental ice was potentially present judging from the significant sea level variations recorded through the latest Paleocene and earliest Eocene. The PETM itself is associated with sea level transgression and a maximum flooding. Finally, based on high-accumulation rate neritic deposits, the onset of the *Apectodinium* acme precedes the onset of the PETM global warming by some 4 kyr, which, in turn leads the CIE by ~3 kyr. Hence, sea surface conditions characteristic of the PETM, including extreme warming, initiated significantly prior to the injection of ^{12}C-enriched carbon. This implies that this injection likely occurred as a result of global change, rather than the other way around, and invokes the dawn of the next challenge: solving the question how global change, including warming, could occur without a change in the isotopic composition of the exogenic carbon pool.