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Cretaceous–Palaeogene ocean and climate change in the subtropical North Atlantic

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Abstract: Ocean Drilling Program (ODP) Leg 171B recovered continuous sequences that yield evidence for a suite of 'critical' events in the Earth's history. The main events include the late Eocene radiolarian extinction, the late Palaeocene benthic foraminiferal extinction associated with the Late Palaeocene Thermal Maximum (LPTM), the Cretaceous–Palaeogene (K–P) extinction, the mid-Maastrichtian event, and several episodes of sapropel deposition documenting the late Cenomanian, late Albian and early Albian warm periods. A compilation of stable isotope results for foraminifera from Leg 171B sites and previously published records shows a series of large-scale cycles in temperature and $\delta^{13}C$ trends from Albian to late Eocene time. Evolution of $\delta^{18}O$ gradients between planktic and benthic foraminifera suggests that the North Atlantic evolved from a circulation system similar to the modern Mediterranean during early Albian time to a more open ocean circulation by late Albian–early Cenomanian time. Sea surface temperatures peaked during the mid-Cretaceous climatic optimum from the Albian–Cenomanian boundary to Coniacian time and then show a tendency to fall off toward the cool climates of the mid-Maastrichtian. The Albian–Coniacian period is characterized by light benthic oxygen isotope values showing generally warm deep waters. Lightest benthic oxygen isotopes occurred around the Cenomanian–Turonian boundary, and suggest middle bathyal waters with temperatures up to 20 °C in the North Atlantic. The disappearance of widespread sapropel deposition in Turonian time suggests that sills separating the North Atlantic from the rest of the global ocean were finally breached to sufficient depth to permit ventilation by deep waters flowing in from elsewhere. The Maastrichtian and Palaeogene records show two intervals of large-scale carbon burial and exhumation in the late Maastrichtian–Danian and late Palaeocene–early Eocene. Carbon burial peaked in early Danian time, perhaps in response to the withdrawal of large epicontinental seas from Europe and North America. Much of the succeeding Danian period was spent unroofing previously deposited carbon and repairing the damage to carbon export systems in the deep ocean caused by the K–P mass extinction. The youngest episode of carbon exhumation coincided with the onset of the early Eocene Warm Period and the LPTM, and has been attributed to the tectonic closure of the eastern Tethys and initiation of the Himalayan Orogeny.

Cretaceous and Palaeogene marine deposits provide the opportunity to study Earth system processes during partly to entirely deglaciated states. Certain key intervals are marked by rapid climate change and massive carbon input. These intervals are the Late Palaeocene Thermal Maximum (LPTM) and Oceanic Anoxic Events (OAEs) in early Aptian–Albian time and at the Cenomanian-Turonian boundary. These time intervals are particularly significant to current earth science objectives because focused research has the potential to considerably improve the understanding of the general dynamics of the Earth's climate during rapid perturbation of the carbon cycle.

Deep ocean sections that are continuously cored provide the high-resolution records to document complex sequences across unique

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events in the geological record that show global biogeochemical variations. These records are needed to register major steps in climate evolution: burial of excess carbon, changes in global temperatures, nutrient cycling, etc. Stable isotope records are fundamental in showing the sequence of events and the amplitude of change in the system. Most Cretaceous stable isotope records are based on bulk carbonate. Here, we present a compilation of known planktonic and benthic foraminiferal stable isotope records to highlight long-term trends in surface and deep ocean palaeoceanography. We present this stable isotope record to provide a palaeoceanographic context to the 14 papers presented in this Special Publication. Several portions of the stable isotope record were compiled from Ocean Drilling Program (ODP) Leg 171B results. This ODP Leg was dedicated to drill Cretaceous–Palaeogene sequences at Blake Nose, northwestern Atlantic, in 1998. The scientific crew on the *JOIDES Resolution* decided to compile a set of papers based on drilling results, in a Special Publication of the Geological Society of London. The focus would be western Atlantic Cretaceous–Palaeogene palaeoceanography and the results are now in front of you. Before we present the compilation of stable isotope results, we would like to introduce you to ODP Leg 171B drilling results.

Ocean Drilling Program Leg 171B drilling

ODP Leg 171B was designed to recover a series of 'critical boundaries' in the Earth's history during which abrupt changes in climate and oceanography coincide with often drastic changes in the Earth's biota. Some of these events, such as the Cretaceous–Palaeogene (K–P) extinction and the late Eocene tektite layers, are associated with the impacts of extraterrestrial objects, such as asteroids or meteorites, whereas other events, including the benthic foraminifer extinction in the late Palaeocene and mid-Maastrichtian events, are probably related to intrinsic features of the Earth's climate system. Three of the critical intervals, early Eocene, the Cenomanian–Turonian boundary interval and the late Albian, are characterized by unusually warm climatic conditions when the Earth is thought to have experienced such extreme warmth that the episodes are sometimes described as 'super-greenhouse' periods. The major objectives of Leg 171B were to recover records of these critical boundaries, or intervals, at shallow burial depth where microfossil and lithological information would be well preserved, and to drill cores along a depth transect where the vertical structure of the oceans during the boundary events could be studied. The recovery of sediments characterized by cyclical changes in lithology in continuous Palaeogene or Mesozoic records would help to establish the rates and timing of major changes in surface and deep-water hydrography and microfossil evolution.

Accordingly, five sites were drilled down the spine of the Blake Nose, a salient on the margin of the Blake Plateau where Palaeogene and Cretaceous sediments have never been deeply buried by younger deposits (Fig. 1). The Blake Nose is a gentle ramp that extends from *c.* 1000 to *c.* 2700 m water depth and is covered by a drape of Palaeogene and Cretaceous strata that are largely protected from erosion by a thin veneer of manganiferous sand and nodules. We recovered a record of the Eocene and Palaeocene epochs that, except for a few short hiatuses in mid-Eocene time, is nearly complete. Thick sequences through the Maastrichtian, Cenomanian and Albian sequences have allowed us to create high-resolution palaeoclimate records from these periods. The continuous expanded records from Palaeogene and Cretaceous time show Milankovitch-related cyclicity that provides the opportunity for astronomical calibration of at least parts of the time scale, particularly when combined with an excellent magnetostratigraphic record and the presence of abundant calcareous and siliceous microfossils. Our strategy was to drill multiple holes at each site as far down as possible to recover complete sedimentary sequences by splicing multisensor track (MST) or colour records.

Lithostratigraphy and seismic stratigraphy of Blake Nose

The sedimentary record at Blake Nose consists of Eocene carbonate ooze and chalk that overlie Palaeocene claystones as well as Maastrichtian and possibly upper Campanian chalk (Fig. 2). In turn, Campanian strata rest unconformably upon Albian to Cenomanian claystone and clayey chalk that appear to form a conformable sequence of clinoforms. A short condensed section of Coniacian–Turonian nannofossil chalks, hardgrounds and debris beds is found between Campanian and Cenomanian rocks on the deeper part of Blake Nose. Aptian claystones are interbedded with Barremian periplatform debris, which shows that the periplatform material is reworked from older rocks. The entire middle Cretaceous and younger sequence rests on a Lower Cretaceous, and probably Jurassic,

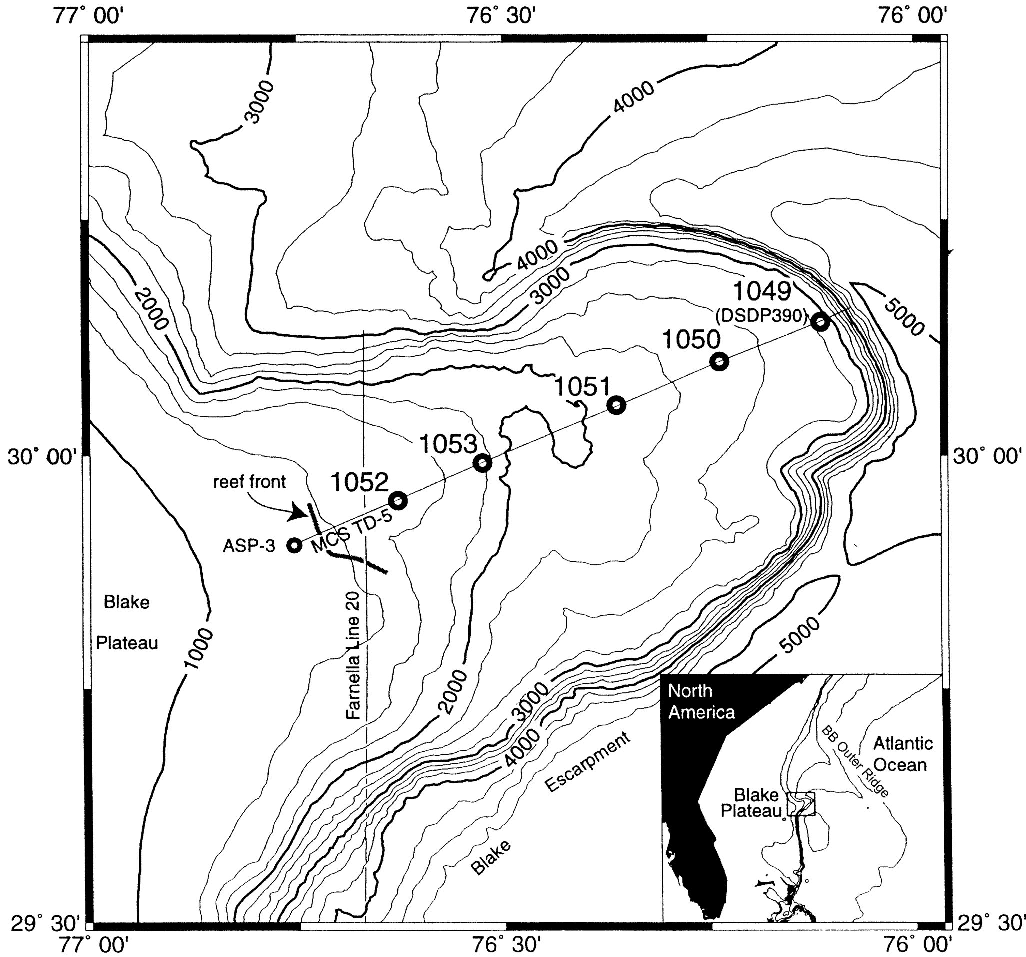

Fig. 1. Location of Blake Nose showing ODP Leg 171B borehole sites and location of Multichannel seismic profile TD-5. BB Outer Ridge, Blake–Bahama Outer Ridge.

carbonate platform that is more than 5 km thick in the region of Blake Nose (Shipley *et al.* 1978; Dillon *et al.* 1985; Dillon & Popenoe 1988).

Seismic records show the presence of buried reef build-ups at the landward end of the Blake Nose (Fig. 3). Fore-reef deposits and pelagic oozes, built seaward of the reef front, rest on relatively flat-lying Barremian shallow-water carbonates and serve largely to define the present bathymetric gradient along Blake Nose (Benson *et al.* 1978; Dillon *et al.* 1985; Dillon & Popenoe 1988). Single-channel seismic reflection data (SCS) lines collected by the *Glomar Challenger* over Deep Sea Drilling Project (DSDP) Site 390 and our reprocessed version of multichannel seismic reflection (MCS) line TD-5 show that more than 800 m of strata are present between a series of clinoforms that overlap the reef complex and the sea bed. ODP Leg 171B demonstrated that most of the clinoform sequence consists of Albian–Cenomanian strata and that a highly condensed sequence of Santonian–Campanian rocks is present in places between the lower Cenomanian and the Maastrichtian sequences (Norris *et al.* 1998). The Maastrichtian section is overlapped by a set of parallel, continuous reflectors interpreted as being of Palaeocene and Eocene age that become discontinuous updip. Most of the Eocene section is incorporated in a major clinoform complex that reaches its greatest thickness down dip of the Cretaceous clinoforms.

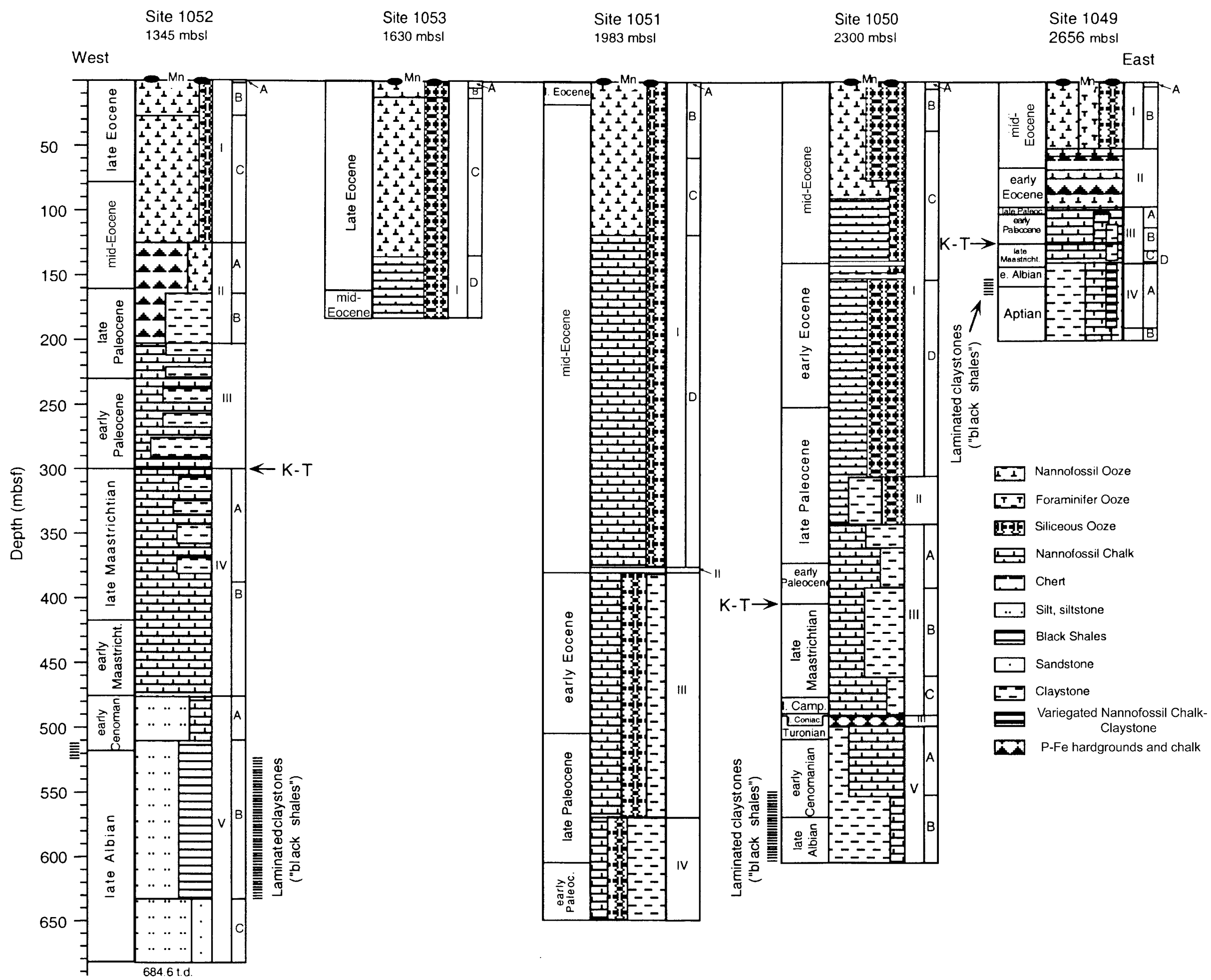

Fig. 2. Simplified lithostratigraphy of ODP Leg 171B sites (after Norris *et al.* 1998).

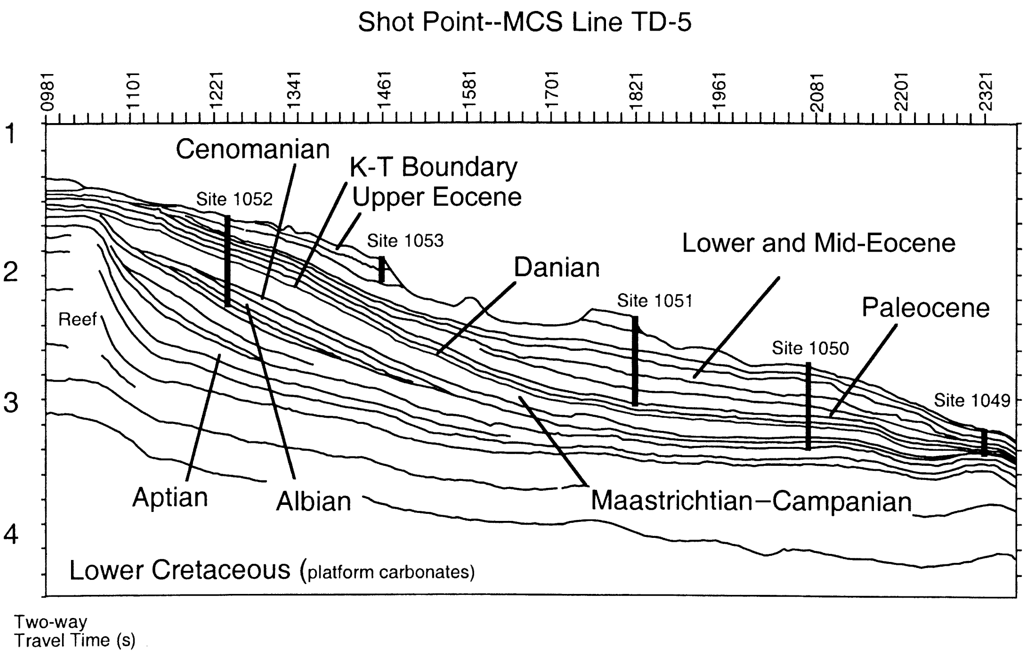

Fig. 3. Schematic interpretation of multichannel seismic profile TD-5 showing ODP Leg 171B drill sites.

Early Albian black shale event (OAE 1b c. 112 Ma)

ODP Leg 171B recovered upper Aptian–lower Albian sediments at Site 1049 consisting of green, red, tan and white marls overlying Barremian and Aptian pelletal grainstones and carbonate sands. A similar succession is present at DSDP Sites 390 and 391 drilled during DSDP Leg 44 as well as in DSDP holes drilled on the Bahama platform. The distal equivalents of these sediments are present at DSDP Site 387 on the Bermuda Rise, where they are light grey limestones interbedded with chert and green or black claystone deposited at water depths of over 4 km (Tucholke & Vogt 1979).

On Blake Nose, the multicoloured claystones contain a single, prominent laminated black shale bed (sapropel) about 46 cm thick (Fig. 4). The sapropel is laminated on a millimetre scale and contains pyrite nodules and thin stringers of dolomite and calcite crystals. Total organic carbon content ranges from *c.* 2 wt % to over 11.5 wt % and has a hydrogen index typical of a type II kerogen (Barker *et al.* this volume). A bioturbated interval of marl about 1 cm thick occurs in the middle of the black sapropel. The lower contact of the sapropel is gradational into underlying green nannofossil claystone. In contrast, the upper contact is sharp below bioturbated olive green nannofossil claystone. The planktonic foraminifer assemblage (characteristic of the upper *Hedbergella planispira* Zone) together with the nannoflora (representing biozone CC7c) suggest an early Albian age and a correlation with OAE 1b.

Ogg *et al.* (1999) estimated sedimentation rates during and after deposition of the OAE 1b sapropel. Spectral analysis of physical property records suggests that the dominant colour cycles (between red, green and white marls) are probably related to the eccentricity and precession cycles and yield average sedimentation rates of *c.* 0.6 cm ka^{-1} across the OAE. Sapropel deposition persisted for at least *c.* 30 ka (Ogg *et al.* 1999). This duration for OAE 1b is probably an underestimate, as it is common for organic matter in sapropels to be partly removed once oxic conditions return to the sea floor (e.g. Mercone *et al.* 2000). Therefore, the OAE 1b sapropel may originally have been thicker and represented a longer period of disaerobic seafloor conditions than is at present the case.

By any measure, the OAE 1b sapropel represents a remarkably long interval of disaerobic conditions. Sapropels formed during Plio-Pleistocene time in the Mediterranean basins were deposited on time scales of no more than a few thousand years (e.g. Mercone *et al.* 2000). The best studied example of OAE 1b in Europe is the Niveau Paquier in the Southeast France Basin. There, the upper Aptian–lower Albian sequence

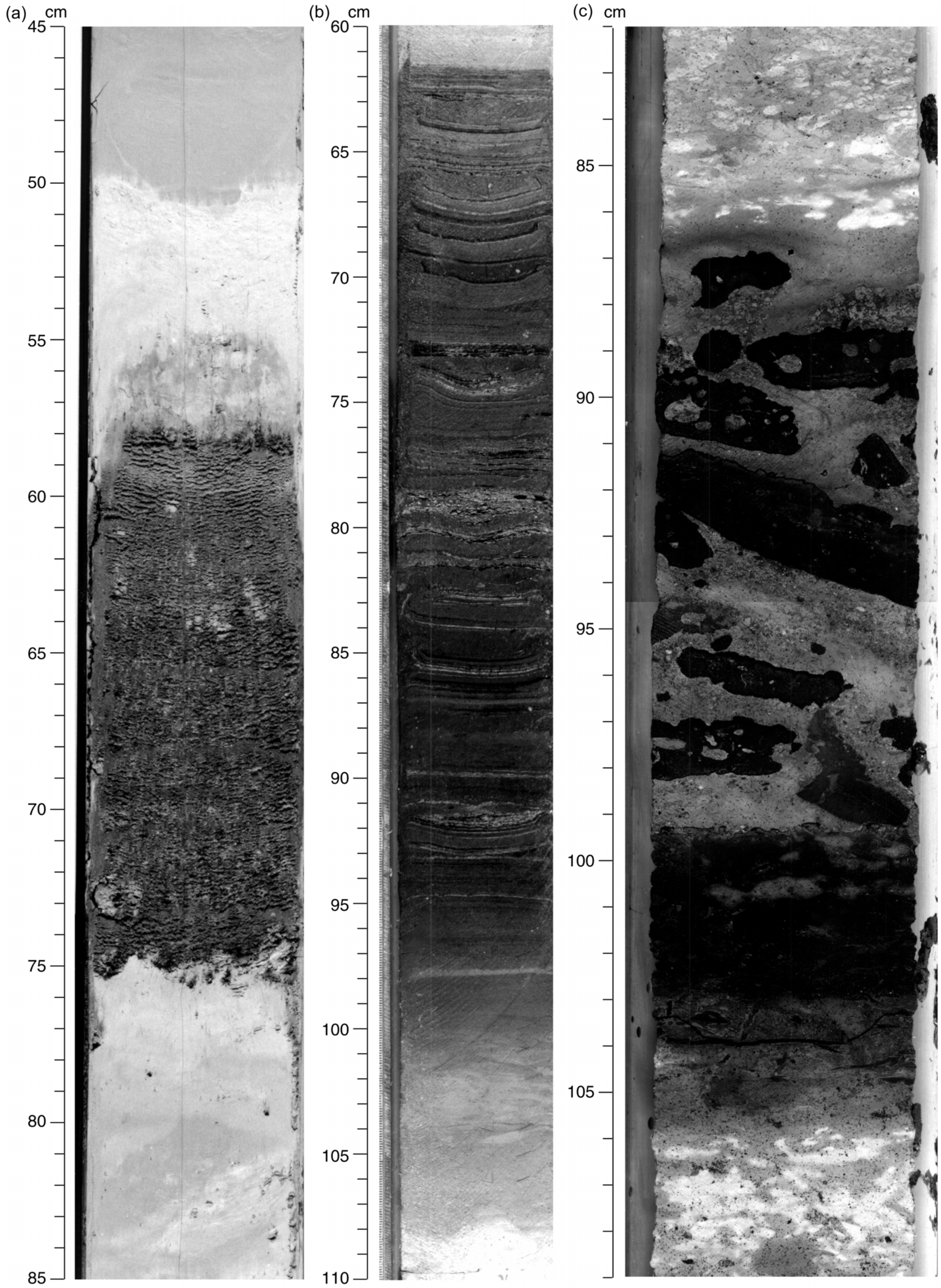

Fig. 4. Conspicuous beds recovered during ODP Leg 171B. (**a**) Close-up of the K–P boundary in Hole 1049A showing the spherule bed that is interpreted as ejecta material from Chicxulub. (**b**) Close-up of the lower Albian black shale that is time equivalent to Oceanic Anoxic Event 1b. (**c**) Condensed section separating sediments of Campanian age (above) and Santonian age (below), from Hole 1050C.

is characterized by numerous black shales, all of which, with the exception of OAE 1b, are not present at Blake Nose. On the basis of the ecology and distribution of benthic foraminifers, Erbacher *et al.* (1999) demonstrated the synchroneity of OAE 1b between Blake Nose and France.

The distribution of the foraminifera was extensively studied across OAE 1b by Erbacher *et al.* (1999) and Holbourn & Kuhnt (this volume). Sediments deposited before OAE 1b contain a low-diversity fauna of opportunistic phytodetritus feeders: foraminifera that feed on the enhanced carbon flux to the ocean floor. This unique fauna replaced a highly diverse fauna and is indicative of the large environmental changes leading to the OAE 1b. The finely laminated black shale itself contains a very impoverished microbiota indicating disaerobic conditions at the sea floor. Although faunal turnovers have been found to be associated with the OAEs, Holbourn & Kuhnt (this volume) concluded from their foraminiferal distributional study that there were no foraminiferal extinctions associated with OAE 1b.

Erbacher *et al.* (in press) showed new stable isotope data on foraminifera from early Albian OAE 1b. Those workers demonstrated that the formation of OAE 1b was associated with an increase in surface-water runoff, and a rise in surface temperatures, that led to decreased bottom-water formation and elevated carbon burial in the restricted basins of the North Atlantic. The stable isotope record has similar features as the Mediterranean sapropel record from the Pliocene–Quaternary period inasmuch as there is a large negative shift in $\delta^{18}O$ of planktic foraminifera in both instances that probably reflects the freshening and perhaps temperature rise associated with the onset of sapropel formation. However, the geographical extent of the OAE 1b is much larger and its duration is at least four times longer than any of the Quaternary sapropels. Hence, current results suggest that OAE 1b was associated with a pronounced increase in surface-water stratification that effectively restricted overturning over a large portion of Tethys and its extension into the western North Atlantic.

Mid-Cretaceous sea surface temperatures and OAE 1d and 2

A thick section of Albian–Cenomanian continental slope and rise sediments were recovered in Holes 1050C and 1052E on Blake Nose. In Hole 1052E, 215 m of black and green laminated claystone, minor chalk, limestone and sandstone were recovered, representing the uppermost Albian and lowermost Cenomanian interval. Sandstones recovered at the base of the hole give way to dark claystones with laminated intervals and thin bioturbated limestones higher in the sequence. A partly correlative sequence was recovered in Hole 1050C where the section starts in latest Albian time and continues through most of Cenomanian time. The Turonian, Santonian and Coniacian periods are represented in a highly condensed sequence of multi-coloured chalk just above the last black shales and chalks of the Cenomanian sequence.

The upper Albian–lower Cenomanian strata in Hole 1052E preserve a biostratigraphically complete sequence from calcareous nannofossil Zone CC8b to CC9c (planktonic foraminifer biozones *Rotalipora ticinensis* to *R. greenhornensis*). The time scales of Gradstein *et al.* (1995) and Bralower *et al.* (1997a) and the biostratigraphy from Site 1052 suggest the sequence records *c.* 8 Ma of deposition between *c.* 94 and *c.* 102 Ma. Sedimentation rates drop off dramatically in the upper *c.* 25 m of the Cenomanian sequence about 98 Ma. The remainder of the sequence was deposited within a 2 Ma interval at sedimentation rates of about 9–10 cm ka^{-1}. The termination of these high sedimentation rates coincides with a lithological change from black shale to chalk deposition, probably reflecting the sea-level rise in early Cenomanian time.

The section across the Albian–Cenomanian boundary in Hole 1052E is correlative with OAE 1d. Black and green shales become increasingly well laminated and darker in colour approaching the Albian–Cenomanian boundary and are accompanied by interbeds of white to grey limestone. High-resolution resistivity (Formation Microscanner; FMS) logs from Hole 1052E demonstrate that the OAE is not a single event, but represents a gradual intensification of the limestone–shale cycle that terminated abruptly at the end of the OAE (Kroon *et al.* 1999; Fig. 5).

Cyclostratigraphy suggests there is a low-frequency cycle (seen best in the unfiltered FMS log) with a wavelength of *c.* 9–10 m that is expressed in cycles of increasing and then decreasing FMS amplitude. In turn, the 10 m cycle consists of bundles of 1.8–2 m cycles. Filtering the FMS record (that is sampled at better than 1 cm resolution) with a 70 cm–20 m window reveals these dominant cycles clearly. There is a still higher frequency cycle about 10–15 cm wavelength that is particularly well expressed in the claystone interbeds and are expressed by high FMS resistivity. These high-resistivity claystones contrast with the low resistivity of more carbonate-rich beds, including the limestone beds that

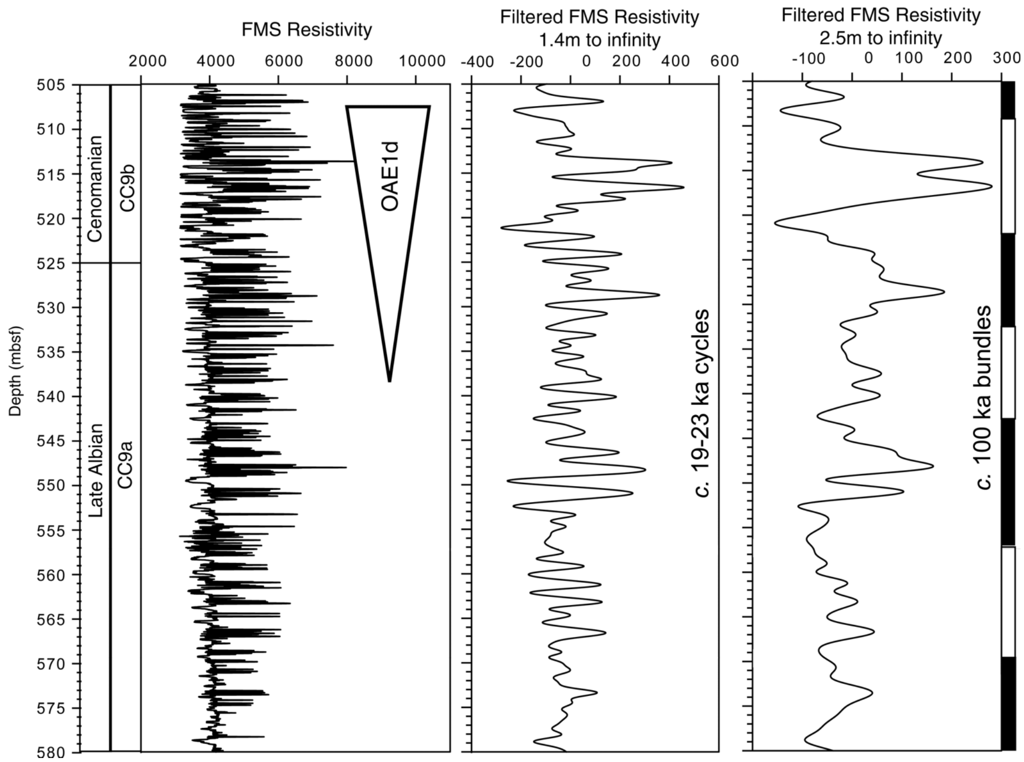

Fig. 5. High-resolution resistivity (FMS) log of ODP Hole 1052E (modified after Kroon *et al.* 1999). The interval shown is characterized by black shale formation paced by orbital cycles. The black shales are characterized by resistivity maxima. Lower frequencies of the Milankovitch spectrum can be observed in the upper part of the record. The record has been filtered (two panels to the right) to emphasize the low-frequency cycles. We interpret the 10 m cycle to be an expression of the eccentricity cycle (100 ka) and the 2 m cycle to be the precessional band (~21 ka).

are prevalent in the interval around the Albian–Cenomanian boundary.

The ratios of the 10 and ~ 2 m cycles are about right to represent the 100 ka and *c.* 21 ka bands of orbital precession (Fig. 5). The higher-frequency cycles do not correspond neatly to orbital bands. We suggest that either our initial guess is wrong that the longer-wavelength cycles represent eccentricity or differential compaction around the limestone stringers has altered the relative spacing of cycles sufficiently to obscure the duration of the high-frequency cycles. However, if we assume that the low-frequency cycle is in the eccentricity band, we can estimate an average sedimentation rate of *c.* 9.0–10.0 cm ka^{-1}. The whole interval represented by the increasing cycle amplitude to the termination of the OAE (between *c.* 575 and 506 mbsf (metres below sea floor)) represents a little over a 750 ka interval of which the peak of OAE 1d lasts for *c.* 400 ka of earliest Cenomanian time.

Norris & Wilson (1998) have shown that the planktonic foraminifera found in the shale beds are extremely well preserved and record an original stable isotopic signature of the oceans across OAE 1d. They found that the subtropical North Atlantic had sea surface temperatures on average warmer than today at between 30 and 31 °C. Temperatures peaked at about the level (*c.* 510 mbsf) where the maximum amplitude of the FMS cycle is also recorded. Apparently the increase in intensity of the OAE was directly mirrored by a rise in surface temperatures. Temperature and the vertical thermal gradient both collapsed near the termination of the OAE, suggesting a fundamental change in ocean circulation and stratification near or at the end of OAE 1d.

The Cenomanian–Turonian boundary interval was investigated at Site 1050 at Blake Nose by Huber *et al.* (1999). This important interval is characterized by one of the major Cretaceous

Anoxic Events (OAE 2). Although the sequence at Site 1050 is not entirely complete, Huber *et al.* (1999) were able to measure stable isotopes of unaltered calcareous planktonic and benthic foraminifera across the Cenomanian–Turonian transition. One of the astonishing results is the massive warming of middle bathyal temperatures based on benthic oxygen isotope results. Bathyal temperatures were already rather high (15 °C) before the boundary but rose to about 19 °C within OAE 2. This deep-water warming does not seem to be mirrored by sea surface water temperatures and therefore (Huber *et al.* 1999) concluded that most heat during OAE 2 time, a super-greenhouse event, was transported via the deep ocean. The warming may have been responsible for the extinction of deeper-dwelling planktonic foraminiferal genera such as *Rotalipora*.

Mid-Maastrichtian extinctions and palaeoceanographic events

The calcareous nannofossil stratigraphy shows that the Maastrichtian sediments, although slumped in parts, are biostratigraphically complete (Self-Trail this volume). The mid-Maastrichtian interval is characterized by a series of important biological and palaeoceanographic events. Extinction of deep-sea inoceramid bivalves and tropical rudist bivalves occurred at the same time with geochemical shifts in deep-sea biogenic carbonates and a pronounced cooling of high-latitude surface waters. It is not clear how all these events are related. Blake Nose middle Maastrichtian sediments, although complicated in places by slumping and coring gaps, yield conclusive evidence in the form of stable isotopes from foraminifera and extinctions concerning the subtropical palaeoceanographic evolution of the area. In contrast to cooling at high-latitude sites, Blake Nose surface waters show a temperature rise of about 4 °C (MacLeod & Huber this volume). Blake Nose results highlight regional mid-Maastrichtian differences. The benthic foraminiferal oxygen isotopes do not show a marked shift in mid-Maastrichtian time in contrast to southern Ocean and Pacific stable isotope records. Therefore, MacLeod & Huber (this volume) excluded build up of ice during the course of Maastrichtian time as the force behind the chain of mid-Maastrichtian events, although the details of mid-Maastrichtian palaeoceanography and cause of extinctions remain enigmatic.

Cretaceous–Palaeogene boundary impact

The ODP Leg 171B recovered a conspicuous Cretaceous–Palaeogene (K–P) boundary interval at Blake Nose (Fig. 4). At the deepest Site 1049 three holes were drilled through the K–P interval. The boundary layer, mostly consisting of green spherules, was interpreted to be of impact origin and ranges in thickness from 6–17 cm in the three holes at Site 1049. The largely variable thickness suggests reworking of the ejecta material down slope after deposition. Martínez-Ruiz *et al.* (this volume *a* & *b*) have shown that the green spherules represent the diagenetically altered impact ejecta from Chicxulub. Martínez-Ruiz *et al.* (this volume *b*) described the now predictive sequence of meteorite debris and associated chemistry across the K–P boundary at Blake Nose: the impact-generated coarse debris or tektite bed is followed by fine-grained pelagic ooze of the earliest Danian period rich in iridium.

One of the remarkable features of the pre-impact sediments at Blake Nose is deformation and large-scale slope failures probably related to the seismic energy input from the Chicxulub impact, some of it clearly induced before the emplacement of the ejecta from the impact (Norris *et al.* 1998; Smit 1999; Klaus *et al.* 2000). Mass wasting as a response to the impact occurred at a large scale. Correlation between Blake Nose cores and seismic reflection data indicates that the K–P boundary immediately overlies seismic facies characteristic of mass wasting (Klaus *et al.* 2000). Sediments 1600 km away from the Chicxulub impact on the Bermuda Rise were 'shaken and stirred'. Norris *et al.* (this volume) found that the seismic reflector associated with mass wasting at the K–P boundary is found over nearly the entire western North Atlantic basin, suggesting that much of the eastern seaboard of North America had catastrophically failed during the K–P impact event. Norris *et al.* (unpubl. data) made a survey of rise and abyssal sediment cores off North America, Bermuda and Spain, and concluded that indeed mass wasting may well have disrupted pelagic sedimentation at the K–P boundary in all those places.

The biostratigraphy of the K–P interval at Blake Nose is typical of an Atlantic seaboard deep-sea K–P section (Norris *et al.* 1999). Ooze immediately below the spherule bed contains characteristic late Maastrichtian planktonic foraminifera and nannofossils. The ooze above the spherule bed contains abundant extremely small Palaeocene planktic foraminifers in addition to large Cretaceous foraminifera. Norris *et al.* (1999) argued that the large Cretaceous planktonic foraminifera found in Darian sediments have been reworked. Small specimens of the same Cretaceous species are hardly present in the post-impact ooze, which implies that some form of sorting has changed the usual size distribution of planktonic foraminifera, which tends to be dominated by small individuals in pelagic sediments. The important conclusion is that the impact ejecta exactly coincided with the biostratigraphic K–P boundary and the planktonic foraminiferal extinction was caused by the Chicxulub impact.

Late Palaeocene Thermal Maximum

Drilling at Blake Nose recovered a continuous sequence of the Palaeocene–Eocene transition at a relatively low-latitude site. The upper Palaeocene section at Site 1051 consists of greenish grey siliceous nannofossil chalk that exhibits a distinctive colour cycle between 23–29 cm wavelength in Palaeocene time and *c.* 1 m wavelength in latest Palaeocene and early Eocene time. A distinctive bed of angular chalk clasts, now deformed by compaction, occurs at about the level at which the increase in colour cycle wavelength is seen. Norris & Röhl (1999) found that the LPTM as defined by a *c.* 2–3‰ $\delta^{13}C$ excursion and the appearance of a distinctive 'excursion fauna' of planktic foraminifera occurs just above the chalk breccia. Furthermore, Katz *et al.* (1999) found the extinction of an assortment of cosmopolitan benthic foraminifera in site 1051 that are also known to have become extinct at the LPTM in other regions around the world. Hence, we are confident that we recovered a section typical of the LPTM on Blake Nose.

Bains *et al.* (1999), Katz *et al.* (1999) and Norris & Röhl (1999) have interpreted the chalk breccia horizon, and step-like features in the $\delta^{13}C$ anomaly as strong evidence that the LPTM was associated with rapid release of buried gas hydrates. Oxidation of released methane to CO_2 would have caused a rapid increase of this greenhouse gas in the atmosphere and thus resulted in warming of the planet. Bains *et al.* (1999) showed that the onset of the carbon isotope anomaly occurred in a series of three pronounced drops in $\delta^{13}C$ separated by plateaux (Fig. 6). They interpreted the steps and intervening plateaux in $\delta^{13}C$ as intervals of rapid methane outgassing separated by intervals where the rate of carbon burial roughly balanced its rate of release into the ocean and atmosphere. Katz *et al.* (1999) showed that the chalk clast breccia can be reasonably interpreted as a debris flow produced by methane hydrate destabilization and venting during the initial phases of the LPTM.

The continuous sequence of Blake Nose across the Late Palaeocene Thermal Maximum (LPTM) displays very pronounced cyclicity of the sediments shown in spectral reflectance records at Site 1051. The carbon isotope anomaly within C24r coincides with a major shift in lithology and cyclicity of various physical property records including sediment colour, carbonate content and magnetic susceptibility. Norris & Röhl (1999) used the cyclicity to provide the first astronomically calibrated date for the LPTM (*c.* 54.98 Ma) and a chronology for the event itself using the Milankovitch induced cyclostratigraphy at Site 1051. Kroon *et al.* (1999) showed that the LPTM may be part of a long-term climatic cycle with a wavelength of 2 Ma by using the downhole gamma-ray log (Fig. 7). The LPTM or carbon anomaly coincides exactly with one of the gamma-ray maxima, possibly showing increased influx of terrigenous clay or less dilution by relatively reduced carbonate content.

Dickens (this volume) reported the results of a numerical modelling study designed to evaluate the potential range for the mass of carbon released. Using the $\delta^{13}C$ record from Site 1051 as the target site, he used a simple box model to assess the implications of variations in the mass and/or isotopic composition of the primary carbon fluxes and reservoirs. Dickens (2000*b*) concluded that a massive release of 1800 Gt of methane hydrate explains best the carbon isotope excursion.

Palaeocene–Eocene climate variability

The Eocene sequence consists largely of green siliceous nannofossil ooze and chalk. The upper part of the sequence is typically light yellow, and the colour change to green sediments below is sharp. This colour change is diachronous across Blake Nose and probably relates to a diagenetic front produced by flushing the sediment with sea water. Planktonic foraminifers, radiolarians and calcareous nannofossils are well preserved throughout most of the middle Eocene sequence, but calcareous fossils are more overgrown in the lower middle Eocene and lower Eocene sequence. A distinct feature of the Eocene sequence is a high number of vitric ash layers that were found at each site. These ash layers can be correlated across and serve as anchor points within the highly cyclical (at the Milankovitch scale) sequences. One of the conspicuous dark upper Eocene layers at Site 1053 contains nickel-rich spinels, which indicates that this layer contains potentially extraterrestrial material as a consequence of the Chesapeake Bay impact (Smit, pers. comm.). The Palaeocene and lower Eocene sediments are relatively clay rich compared with the middle and upper Eocene deposits. The

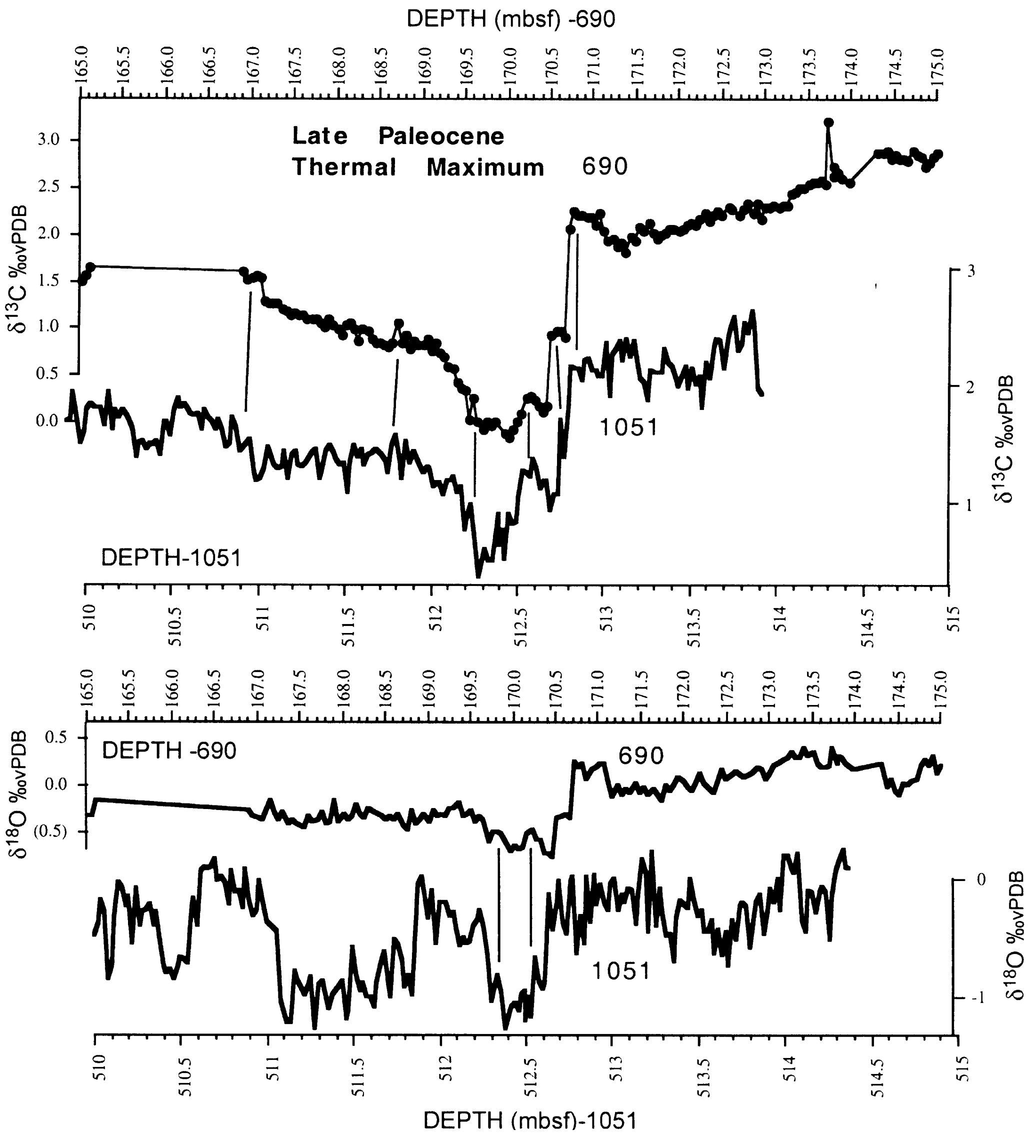

Fig. 6. High-resolution (*c.* 1–2 cm spacing) stable isotope records of bulk carbonate across the LPTM at ODP Site 1051 (Blake Nose, western North Atlantic) and ODP Site 690 (Southern Ocean) after Bains *et al.* (1999). Noteworthy features are the close correlation that can be achieved during the LPTM despite the considerable difference in location of the two sites, and the set of 'steps' leaving to the most negative $\delta^{13}C$ during the onset of the LPTM. These 'steps' suggest that ^{12}C was introduced into the biosphere in a series of rapid pulses separated by intervals of approximate balance between outgassing and carbon burial. Bains *et al.* (1999) proposed that the 'steps' reflect massive failure of methane hydrate reservoirs.

upper Palaeocene sequence contains chert or hard chalk, and preservation of most fossil groups is moderate to poor. The lower Palaeocene sediment is typically an olive green, clay-rich nannofossil chalk or ooze. Calcareous microfossils are typically very well preserved, whereas siliceous components are absent.

A number of excellent biostratigraphic studies have developed from the Blake Nose Palaeogene records. The preservation of the mid- and late Eocene calcareous fossils is very good and the preservation of the siliceous fossils is adequate to construct a detailed biostratigraphy, one of the first for late Palaeocene and early Eocene time.

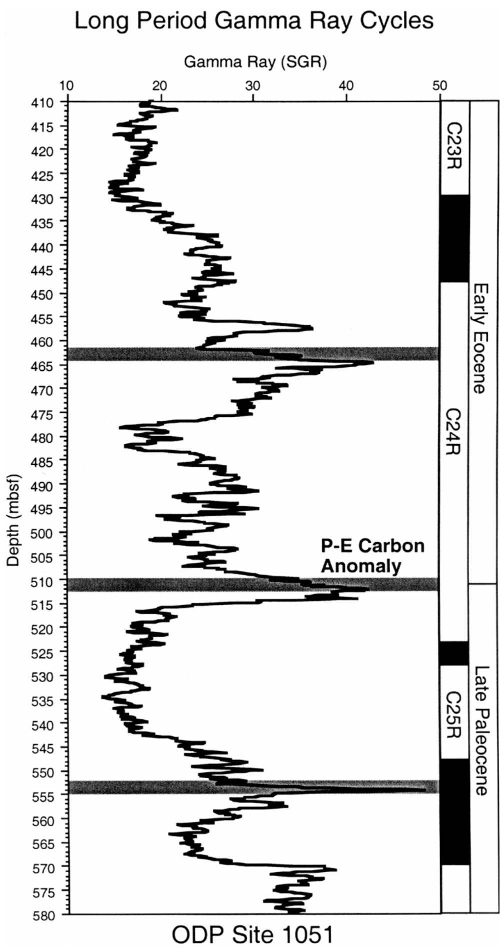

Fig. 7. Downhole gamma-ray log of Site 1051. (Note the long wavelength of *c.* 2 Ma in the gamma-ray record.) One of the maxima in Chron C24R coincides with the LPTM carbon isotope anomaly (modified after Kroon *et al.* 1999).

Also, the organic-walled fossils including the dinoflagellate cysts appear to be very useful. The good preservation of both carbonate and siliceous microfossils led to the first well-integrated biostratigraphy of mid-latitude faunas and floras (Sanfilippo & Blome this volume). The sedimentary sequence is unique in containing well-preserved radiolarian faunas of late early Palaeocene to late mid-Eocene age. Sanfilippo & Blome (this volume) have documented 200 radiolarian biohorizons. Middle to Upper Eocene sediments contain dinocyst assemblages characteristic of warm to temperate surface waters (van Mourik *et al.* this volume). The absence of known cold-water species shows there was no influence of a northern water mass in the area of Blake Nose and thus subtropical conditions prevailed throughout mid–late Eocene time.

One of the main objectives for drilling Blake Nose was to recover complete sequences of Palaeogene sediments by drilling multiple holes. The recovery of continuous sequences characterized by cyclical changes in lithology would help to establish the rates and timing of major changes in surface and deep-water hydrography. Röhl *et al.* (this volume) have presented a study on the use of Milankovitch forcing of sediment input, expressed in the periodicity of iron (Fe) concentrations, to calculate elapsed duration of the Danian stage. A new astronomical Danian time scale emerged from counting obliquity cycles at Sites 1050C and 1001A (Caribbean Sea), which surprisingly appeared to be the dominant frequency in the record. Röhl *et al.* elegantly made use of the Fe records observed in the cores and various downhole logs to fill in for drilling gaps. The results from both drilling sites were neatly similar. Analysis of the cyclostratigraphy both from the cores and downhole logs appears to be successful in the older parts of the stratigraphy and useful in calibrating magnetic polarity zones.

Wade *et al.* (this volume) have presented the first detailed benthic and planktonic foraminiferal oxygen isotope curves in combination with spectral reflectance records from late mid-Eocene time. Those workers found clear evidence of Milankovitch cyclicities at Site 1051 (Fig. 8; Wade *et al.* this volume). At Site 1051 in the top 30 m, the colour records document a dominant cyclicity with wavelengths of 1.0–1.4 cycles m^{-1} forced by precession (Fig. 8), whereas the stable isotope records demonstrate all frequencies of the Milankovitch spectrum. Changes in the $\delta^{18}O$ records of the surface-dwelling planktonic foraminifera are astonishingly large. Wade *et al.* (this volume) concluded that upwelling variations may be responsible for these large variations resulting in large sea surface temperature variations. Sloan & Huber (this volume) in a modelling study also found that changes in wind-driven upwelling and in continental runoff on a precessional time scale should be observed in regions of the central North Atlantic.

Another subject relates to the distribution of clay minerals. One of the most exciting aspects is that the origin of palygorskite clay minerals found in lower Eocene pelagic sediments in the western Central Atlantic may be authigenic (Pletsch this volume). Of particular interest and greater potential significance is the idea that authigenic palygorskite formation required the presence of relatively saline bottom waters, such as the elusive 'Warm Saline Bottom Water'

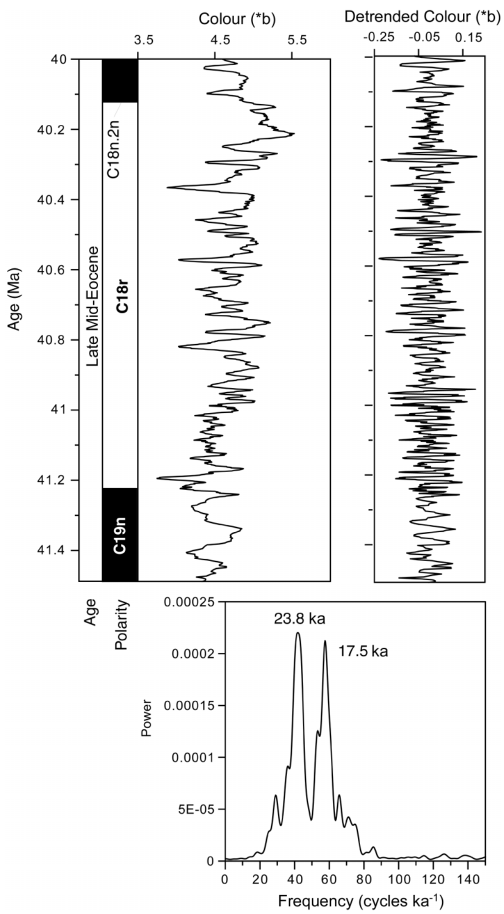

Fig. 8. Cyclostratigraphy for late mid-Eocene time from ODP Site 1051. The colour cycle has been assigned an age scale based on magnetic polarity datum points and detrended with a 50 point moving average (right panel) to draw out the high-frequency cycle periods. Spectral analysis of the resulting detrended record is shown below and suggests that the main cycles correspond approximately to the precession bands.

(WSBW) of Brass *et al.* (1982). As such the distribution of palygorskite could become a palaeo-watermass tracer of WSBW.

A Cretaceous–Palaeogene stable isotope record

Palaeoclimate records of the Mesozoic and Cenozoic eras display a long-term trend from extremely warm conditions during the mid-Cretaceous optimum to cooler climates of late Palaeogene and Neogene time. The Neogene climate record is reasonably well known on a time scale of *c.* 50–100 ka resolution or better, based on extensive surveys of benthic and planktonic stable isotope stratigraphies from all the major ocean basins save the Arctic. However, Palaeogene and Cretaceous climates are currently poorly resolved owing to the scarcity of high deposition rate sections and the frequent poor preservation of microfossils upon which various faunal and geochemical climate proxies are based. Consequently, most of our highly resolved records of Cretaceous and Palaeogene climate come from stable isotope analyses of bulk carbonates. The uncertain role of diagenesis in these isotopic data has made it difficult to draw firm conclusions about many aspects of ocean climate and circulation.

To improve the situation we have combined stable isotope records from Leg 171B sites with previously published datasets to illustrate long-term trends in $\delta^{18}O$ and $\delta^{13}C$ for the surface and deep ocean (Fig. 9). These data include records of planktonic foraminifera that record the most negative $\delta^{18}O$ as well as benthic species to show the vertical $\delta^{18}O$ and $\delta^{13}C$ gradients in the oceans. Currently, there are insufficient data to determine which of the features of these isotope records reflect global trends rather than regional trends for the interval before Campanian time. However, Campanian and younger trends have been duplicated in a number of localities suggesting that the basic patterns are of global significance. Trends in mid-Cretaceous records have been illustrated in several low- to moderate-resolution datasets from both deep-sea and outcrop sections (e.g. Clarke & Jenkyns 1998; Stoll & Schrag 2000). Our foraminifer isotopic records broadly mirror patterns in the bulk sediment stable isotope data. It is likely that parts of the Albian and Cenomanian records will ultimately be found to differ in amplitude and absolute values from deep Pacific or Indian Ocean records. The North Atlantic was partly a silled basin during Albian and Cenomanian time and was part of the Tethys seaway, suggesting that it may have been filled with intermediate waters or even surface waters from elsewhere in the world's oceans.

Cretaceous climatic optimum

Benthic $\delta^{18}O$ in early Albian time was broadly similar to that during the Cretaceous and early Palaeogene time. However, Atlantic intermediate waters (*c.* 1500 m water depth at ODP Site 1049) approached the same $\delta^{18}O$ values as planktonic foraminifera during early Albian time. The convergence of planktonic and benthic $\delta^{18}O$

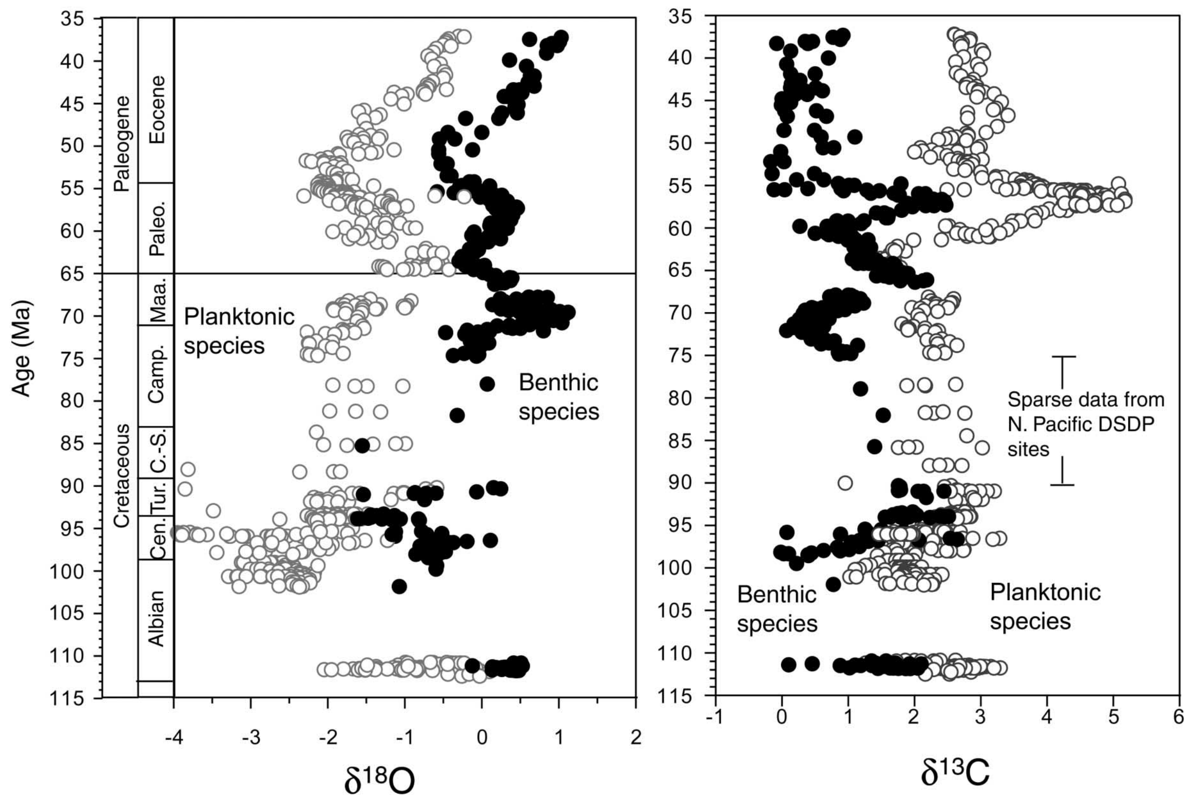

Fig. 9. Compilation of stable isotope records for planktonic foraminifera (○) and benthic foraminifera (●) showing long-term climate trends in the Atlantic and global ocean. Not all the trends shown are strictly global as some, such as the mid-Maastrichtian $\delta^{18}O$ increase in benthic foraminifera, are not observed in the Atlantic and others, such as the various trends in Albian and Cenomanian time may include features unique to the silled basins of the Atlantic. Early Albian data from ODP Hole 1049C (Blake Nose, western North Atlantic; Erbacher *et al.* 2000), late Albian–early Cenomanian data from ODP Site 1052 (Blake Nose, western North Atlantic; Norris and Wilson 1998), Cenomanian–early Turonian data from ODP Hole 1050C (Blake Nose, western North Atlantic; Huber *et al.* 1999, unpubl. data); latest Cenomanian data from DSDP Site 144 (equatorial western Atlantic; Norris *et al.* unpubl. data); Turonian–early Campanian datasets from various North Pacific DSDP sites (mostly DSDP Sites 463, 305 and 311 (Douglas & Savin 1973, 1975, 1978; Barrera 1994)); Maastrichtian and late Campanian data from DSDP Site 463 (equatorial Pacific; Barrera & Savin 1999); Palaeocene data from DSDP Site 384 (northwest Atlantic; Berggren & Norris 1997), and late Palaeocene and Eocene data from ODP Site 865 (north central Pacific; Bralower *et al.*, 1995).

records suggests that the North Atlantic basin was either filled with overturning surface waters or that the planktonic foraminifera chosen for analysis grew in subthermocline waters. We think it most likely that the occasional similarity in deep and surface $\delta^{18}O$ reflects variability in the intensity of surface stratification, as the $\delta^{18}O$ gradient swings between *c*. 0.5‰ and nearly 2‰ during OAE 1b (*c*. 112 Ma). Hence, the isotopic data suggest that the western North Atlantic was probably filled with moderately high-salinity waters not unlike the modern Mediterranean Basin that were occasionally more strongly stratified by runoff from the adjacent continents or by inflow of low-salinity waters from adjacent ocean basins such as the Arctic or the Pacific. Indeed, tectonic reconstructions show that the North Atlantic could have been hydrographically restricted from the deep Indo-Pacific by shallow sills across the Central American Seaway and the myriad of elevated plateaux and tectonic terranes in the Tethys Seaway (Hay *et al*. 1999).

Our isotopic data (Erbacher *et al*. 2000) suggest that the western North Atlantic behaved like the Plio-Pleistocene Mediterranean basins. There, the modern vertical temperature gradient can be as low as 3–4 °C and salinities of *c*. 36‰ increase $\delta^{18}O$ of planktonic and benthic foraminifera by as much as +1‰ over the open eastern North Atlantic (Miller *et al*. 1970). The potential for unusually high salinities in the North Atlantic during early Albian time makes it difficult to estimate absolute sea surface temperatures (SST). However, heavy $\delta^{18}O$ values from other records (Huber *et al*. 1995; Clarke & Jenkyns 1999) may suggest that temperatures during early Albian time were lower than during any other period in the mid-Cretaceous.

We have no foraminifer $\delta^{18}O$ data from mid-Albian time. Indeed, a survey of existing DSDP and ODP sites suggests that mid-Albian time is very poorly represented everywhere in the deep oceans, or where present, has little calcareous fossil material suitable for stable isotopic analysis. The situation changed by the late Albian, where isotopic results from ODP Hole 1052E show that both planktonic and benthic $\delta^{18}O$ were nearly the most negative ratios seen in the last 100 Ma. Only around the Cenomanian–Turonian boundary interval can lighter isotopic values be observed. The large vertical $\delta^{18}O$ gradients between planktonic and benthic foraminifera suggest that by late Albian time, the North Atlantic had ceased to be an extension of a silled Tethys Seaway with an estuarine circulation and had developed deeper marine connections to other deep ocean basins.

Norris & Wilson (1998) inferred that SST reached at least 30–31 °C during late Albian and earliest Cenomanian time (*c*. 98–102 Ma) in the western North Atlantic. These high temperatures were maintained or even raised further during parts of the Cenomanian. For example, planktonic foraminifera from DSDP 144 (9° N) in the equatorial western North Atlantic have average $\delta^{18}O$ values of −3.9‰, equivalent to temperatures of *c*. 32–34 °C using estimates from standard palaeotemperature equations, modern salinity, and assumption of an ice-free world. Notably, benthic $\delta^{18}O$ also peaks in upper Cenomanian time, reaching ratios over 1‰ more negative than that seen at any point in the deep oceans during the Cenozoic. Intermediate waters may have been unusually warm near the C–T boundary (Huber *et al*. 1999). Alternatively, tectonic barriers to exchange with other ocean basins may have become sufficiently restrictive that the North Atlantic was filled with thermocline waters or upper intermediate waters flowing in over shallow sills.

Our data (Huber *et al*. unpubl. data) from ODP Site 1050 illustrate that the mid-Cretaceous thermal optimum was not uniformly warm or stable. A pronounced increase in both planktonic and benthic $\delta^{18}O$ occurred in the mid-Cenomanian during the *Rotalipora reicheli* Zone (*c*. 97 Ma). Stoll & Schrag (2000) recorded a similar event in $\delta^{18}O$ of bulk limestone and marl in outcrop sections from Spain and Italy. They suggested on the basis of the magnitude of the event and its abrupt onset, that it records glaciation and a shift in whole ocean $\delta^{18}O$ as a result of ice build-up. A similar event is present in our data from the middle Cenomanian sequence in ODP 1050 and the $\delta^{18}O$ analyses of bulk carbonates from the Indian Ocean (Clarke & Jenkyns 1999) and Tethys (Stoll & Schrag 2000). Although the widespread occurrence of the $\delta^{18}O$ maxima suggests a global shift in $\delta^{18}O$, such as that produced by ice volume changes, intermediate water palaeotemperatures at this site and in the southern South Atlantic (Huber *et al*. 1995) were none the less higher (>11 °C) than would be expected if there were a significant volume of polar ice unless the North and South Atlantic basins were isolated from high-latitude sources of deep water.

The possible existence of large ice volume changes during the peak of mid-Cretaceous warmth raises questions about mechanisms that regulate ice growth and decay. Huber *et al*. (1995) showed that latitudinal thermal gradients were unusually low during intervals of the mid-Cretaceous thermal optimum. Therefore, it is hard to understand how ice growth could begin when high-latitude SSTs were nearly as high as equatorial temperatures. The abrupt $\delta^{18}O$ swings in Cenomanian time suggest that there may be threshold effects that can dramatically alter ocean circulation and temperature at the warm end of the climate spectrum, in much the same way that feedback systems such as moisture balance and runoff operate to abruptly change boundary conditions in Pleistocene time at the cool end of the climate spectrum.

Campanian–Maastrichtian refrigeration

We have limited stable isotope data for foraminifera from late Turonian to mid-Campanian time, an interval of *c.* 15 Ma. Data are contradictory for this interval. Huber *et al.* (1995) showed that DSDP Site 511 in the South Atlantic was bathed with warm waters from Cenomanian to Coniacian time and SST did not begin to fall appreciably until early Campanian time. Barrera (1994) presented a handful of measurements from North Pacific DSDP sites that also suggest peak temperatures were maintained until some time in the Santonian period. However, $\delta^{18}O$ data of bulk carbonates from Indian Ocean DSDP sites (Clarke & Jenkyns 1999) suggest that the decline in temperatures occurred during late Turonian time. The planktonic foraminifera show a tendency towards heavier isotopic values during the course of the Turonian as suggested by the dataset from ODP Site 1050 (Huber *et al.* unpubl. data), although some extreme light isotopic values can still be seen. Results from Site 1050 suggest that planktonic $\delta^{18}O$ was similar to or more positive than that in late Campanian time and suggest that the surface waters were significantly cooling during Turonian time, although highly variable. One could conclude from the planktonic isotope record that the mid-Cretaceous climatic optimum was over by *c.* 90 Ma if not earlier, although the benthic isotope data show that a persistent fall towards heavier values occurred in Campanian time. More benthic isotope data are needed to document the exact timing of the end of the mid-Cretaceous climatic optimum.

Barrera & Savin (1999) published Campanian and Maastrichtian data for planktonic and benthic $\delta^{18}O$ from a number of sites around the world. Most records show the long-term trend to more positive $\delta^{18}O$ in both surface and deep waters and an abrupt step in this trend about 71 Ma. Miller *et al.* (1999) interpreted the step increase in foraminifer $\delta^{18}O$ to reflect an increase in ice volume and glacioeustatic sea-level lowering. MacLeod & Huber (this volume) have shown that the positive $\delta^{18}O$ deflection in benthic foraminifera is not nearly so pronounced in benthic records from the North Atlantic. Their data suggest either that the $\delta^{18}O$ shift observed elsewhere is not a glacial step or that the North Atlantic record is biased by the introduction of an unusually warm deep water mass that overprints the glacial increase in $\delta^{18}O$. Notably, the size of the mid-Maastrichtian increase in $\delta^{18}O$ in planktonic foraminifera is about a third to half the amplitude of the change in benthic foraminifera even in the Pacific. Therefore, it seems likely that at least half of the mid-Maastrichtian $\delta^{18}O$ shift is due to cooling or an increase in salinity of deep waters.

Cretaceous–Palaeogene boundary and Danian climate

The Cretaceous–Palaeogene (K–P) boundary is preceded by a rise in global ocean $\delta^{13}C$ and bottom-water temperatures starting in mid-Maastrichtian time (*c.* 71–72 Ma) that culminates in early Danian time (Fig. 9). The overall rise in benthic $\delta^{13}C$ and deep-water temperatures probably reflects carbon burial and CO_2 sequestration (Zachos *et al.* 1989; Stott & Kennett 1990). Sea-level fall may have played a role in carbon burial through the formation of large coal swamps with the retreat of epicontinental seas in late Maastrichtian time. The deep-sea $\delta^{13}C$ record is also influenced by a general decrease in inter-basin $\delta^{13}C$ gradients near the end of Maastrichtian time that reduced the isotopic contrast between relatively young deep waters in the North Atlantic and relatively old deep waters in the Pacific and Indian Ocean (e.g. Corfield & Norris 1996, 1998; Barrera & Savin 1999). Frank & Arthur (1999) explained the reduction of interbasinal $\delta^{13}C$ gradients by suggesting that the opening of deep passages between the North and South Atlantic played a key role in ventilating the deep North Atlantic during mid-Maastrichtian time. None the less, the North Atlantic continued to maintain a distinctive young deep and intermediate water-mass through the mid-Palaeocene (Corfield & Norris 1996, 1998).

Bottom temperatures stayed the same or rose from mid-Maastrichtian time to the K–P boundary, whereas surface water temperatures fell until the last 200 ka of the Cretaceous period. The general decline in SST may be related to the withdrawal of epicontinental seas (Frank & Arthur 1999) or to the sequestration of carbon and CO_2 during the rise in global $\delta^{13}C$ in late Maastrichtian time. The deep North Atlantic and deep waters elsewhere in the oceans display distinctly different $\delta^{18}O$ throughout late Maastrichtian time. The North Atlantic was consistently *c*. 2 °C warmer or less saline than the other deep basins, a contrast that was maintained through early Palaeocene time (e.g. Corfield & Norris 1996). Relatively high deep-water temperatures in the North Atlantic may reflect the presence of young deep waters conditioned by overflow from Tethyan basins much like the conditioning of modern North Atlantic deep water by Mediterranean outflow waters.

The early Danian period (64–65 Ma) is best known as a time of tremendous turnover in marine pelagic ecosystems following the Cretaceous–Palaeogene mass extinction (D'Hondt & Keller 1991; Gerstel *et al*. 1987; Jablonski & Raup 1995; Keller 1988; MacLeod 1993; Olsson *et al*. 1992; Smit 1982). The extinction eliminated *c*. 95% of planktonic foraminifer species and had a profound effect on other members of the plankton. The extent of the devastation of the pelagic ecosystem is reflected by the extended (*c*. 3 Ma) collapse of the carbon pump and the vertical $\delta^{13}C$ gradient in the oceans (e.g. D'Hondt *et al*. 1998).

The recovery was also associated with large-scale changes in marine climate and carbon-cycle dynamics. There is a general decrease in global ocean $\delta^{13}C$ that may reflect reduced productivity and carbon burial (Shackleton & Hall 1984). In addition, the vertical $\delta^{18}O$ gradient was greatly reduced for an interval of almost 3 Ma in early Danian time coincident with the reduction in the vertical $\delta^{13}C$ gradient. The declines in vertical $\delta^{18}O$ and $\delta^{13}C$ gradients are both likely to be partly related to reorganization of biotic communities brought on by the end-Cretaceous mass extinction. A reduction in the vertical $\delta^{18}O$ gradient is perhaps best explained by the widespread extinction of surface-dwelling species of planktonic foraminifera during the K–P mass extinction and a tendency for palaeoceanographers to analyse species that grew mostly in thermocline waters during early Danian time.

At the K–P boundary, the mass extinction resulted in a dramatic 1‰ decrease in surface ocean $\delta^{13}C$ with little or no change in deep-water $\delta^{13}C$. The absence of any large negative shift in $\delta^{13}C$ of deep waters strongly suggests that changes in the vertical $\delta^{13}C$ gradient are due to the extinction of surface ocean biota rather than a change in the global $\delta^{13}C$ reservoir (Hsü *et al*. 1982; Zachos & Arthur 1986; Zachos *et al*. 1989; D'Hondt *et al*. 1998). Some records show an inversion of the surface-to-deep $\delta^{13}C$ gradient (Hsü & McKenzie 1985; Zachos & Arthur 1986) that has been attributed to biomass burning (Ivany & Salawitch 1993) but could also reflect measurement artifacts due to low carbonate content in the boundary interval (e.g. Shackleton 1986).

Following the collapse of planktonic and benthic $\delta^{13}C$ gradients during the mass extinction, global $\delta^{13}C$ continues to rise. Maximum benthic $\delta^{13}C$ of *c*. 2.2‰ is recorded less than 100 ka above the K–P boundary and is succeeded by a long-term decline in $\delta^{13}C$ over the next 4 Ma. Hence, it appears that the process of carbon burial that led to the Maastrichtian rise in benthic $\delta^{13}C$ was reversed just after the K–P mass extinction and set in motion a long-term interval of unroofing previously deposited carbon. We suggest that the change from net carbon burial to net erosion may reflect the final draining of epicontinental seas and the onset of weathering of coal and organic shales deposited during late Cretaceous time. By the end of the Danian (*c*. 61 Ma) benthic $\delta^{13}C$ had returned to a ratio very similar to that achieved in mid-Maastrichtian and late Albian time, and very close to that later reached during the early Eocene.

Palaeocene–Eocene climate trends

One of the most striking features of the early Cenozoic and Cretaceous stable isotope records is the dramatic positive shift in $\delta^{13}C$ of both planktonic and benthic foraminifera in late Palaeocene time. Benthic foraminifer $\delta^{13}C$ increased by *c*. 2‰ and planktonic foraminifer $\delta^{13}C$ increased by *c*. 3‰ between 61 and 58 Ma. Part of the increase in $\delta^{13}C$ of planktonic foraminifera is probably due to the re-evolution of photosymbiosis after the K–P mass extinction (e.g. Corfield & Norris 1998). However, the increase in $\delta^{13}C$ of benthic species is seen throughout the oceans (e.g Miller *et al*. 1987; Corfield & Cartlidge 1992), suggesting that it represents a reservoir effect of burying large quantities of organic carbon. It is not at all clear where all this carbon was deposited, as there are few large oil or coal reservoirs of late Palaeocene age. The relatively rapid decline of $\delta^{13}C$ of both benthic and planktonic foraminifera between 58 and 55 Ma suggests that much of the carbon buried during Palaeocene time was exhumed by the end of the Palaeocene epoch. Beck *et al*. (1998) have suggested that much of the carbon deposited during late Palaeocene time may have accumulated in Tethyan basins that were subsequently uplifted and eroded during the initial stages of the Himalayan Orogeny.

The peak of the Palaeocene $\delta^{13}C$ increase coincides with the most positive benthic foraminiferal $\delta^{18}O$ ratios in the Palaeogene period. A modest increase in $\delta^{18}O$ of planktonic foraminifera is also present, suggesting cooling of both surface and deep waters during the late Palaeocene 'carbon isotope maximum'. We speculate that CO_2 drawdown associated with organic carbon burial may have been responsible for the fall in ocean temperatures. Evidence for snowmelt and cool interior climates in the Rocky Mountains (e.g. Dettman & Lohmann 2000) as well as palaeobotanical estimates of mean annual temperature (e.g. Wing 1998) suggest that cooling in late Palaeocene time occurred over the continental interiors as well as the oceans. The late Palaeocene cool phase was succeeded by a *c*. 3 Ma interval of increasingly warm conditions leading up to the Late Palaeocene Thermal Maximum (LPTM) at *c*. 55 Ma.

The LPTM occurred at the point where deep-water temperatures and SST had nearly reached the highest levels in Cenozoic time. Zachos & Dickens (1999) and Katz *et al*. (1999) have proposed that the LPTM occurred because deep-water temperatures exceeded a threshold level above which methane hydrates began to catastrophically destabilize and contribute to a runaway greenhouse effect. However, Bains *et al*. (1999) pointed out that the long-term warming trend in latest Palaeocene time is highly aliased and that detailed $\delta^{18}O$ records from both foraminifera and fine fraction carbonate display no significant warming trend for at least 200 ka before the LPTM. Hence, it is unclear whether the million-year scale drift to higher temperatures has anything to do with the LPTM. Other proposed mechanisms to initiate the LPTM include changes in deep-water circulation inspired by tectonics (Beck *et al*. 1998), volcanism (Eldholm & Thomas, 1993; Bralower *et al*. 1997*b*) or slope failure (Bains *et al*. 1999; Norris & Röhl 1999).

Dickens (1999) suggested that sedimentary carbon reservoirs act as 'capacitors' in the global carbon cycle that store and release greenhouse gases to modulate global climate. This theory supposes that methane dissociation events, as proposed for the LPTM, are common in the geological record (Dickens 2000*b*). Indeed, the example of the LPTM has spawned a resurgence of interest in the Cretaceous and Palaeogene climate record and has led to the discovery of other large perturbations in the carbon cycle. Large negative $\delta^{13}C$ anomalies have been identified with the onset of several Oceanic Anoxic Events (OAEs) in Cretaceous time (Jenkyns 1995; Wilson *et al*. 1999). Likewise, analysis of benthic foraminifer assemblages and isotopic anomalies provides strong hints that there may be other events like the LPTM in late early Eocene and mid-Palaeocene time (Thomas & Zachos 1999). Short, but intense, $\delta^{13}C$ anomalies are of great interest as 'natural experiments' in the biological and climatological effects of transient perturbations of the carbon cycle. The increasing evidence that there may be several LPTM-like events offers the exciting opportunity to compare and contrast these events to better evaluate the palaeoceanographic context, trigger, duration and biological effect of large-magnitude changes in carbon reservoirs of whatever cause. There is also the possibility that some of the $\delta^{13}C$ events represent large emissions of greenhouse gases and can provide natural analogues for modern greenhouse warming.

The early Eocene benthic $\delta^{18}O$ record shows that the Earth was essentially warmer than today. That is to say, the high-latitude oceans were much warmer than today, raising the global mean temperature (e.g. Zachos *et al*. 1994), and the Earth was characterized by the absence of large ice sheets. None the less, maximum sea surface temperatures in the tropics were not necessarily higher than modern temperatures. Most planktonic isotope records show that low-latitude early Eocene sea surface temperatures were lower than at present (Boersma *et al*. 1987; Zachos *et al*. 1994; Bralower *et al*. 1995). This is not well understood. Either heat diffused into the deep ocean or the stable isotope records of the planktonic foraminifera do not record the surface, or have been affected by diagenesis. Wade *et al*. (this volume) have shown that massive upwelling in late mid-Eocene time influenced low-latitude sea surface temperatures. Upwelling at Milankovitch periodicities may explain why sea surface temperature estimates were low in the low latitudes. Towards mid-Eocene time increases in $\delta^{18}O$ can be seen in both the planktonic and benthic foraminiferal records. These trends indicate cooling of the Earth (Kennett & Shackleton 1976) starting near the early Eocene–mid-Eocene transition and continuing in a series of steps to the Eocene–Oligocene boundary.

Conclusions

A number of outstanding post-cruise studies resulted from ODP Leg 171B drilling at Blake Nose in the North Atlantic concerning biostratigraphy, palaeoceanography–palaeoclimatology and meteorite impacts. Here, we have summarized the highlights of these results, which appear in this volume. In addition, we have combined the new planktonic and benthic foraminiferal stable isotope records of ODP Leg 171B with previously published datasets to elucidate the main features of the Cretaceous–Palaeogene oceans. The dataset is still sparse and additional data are needed to confirm the trends described here. Nevertheless, it represents the first long-term stable isotope record solely based on planktonic and benthic foraminifers and gives a unique overview of palaeoceanographic changes and their probable causes during the early stage of the evolution of the Atlantic Ocean.

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