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INTRODUCTION: CRETACEOUS–PALEOGENE CLIMATIC EVOLUTION OF THE WESTERN NORTH ATLANTIC, RESULTS FROM ODP LEG 171B, BLAKE NOSE[1]

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INTRODUCTION

Since its inception in the Triassic, the Atlantic basins have become increasingly integrated with the global ocean. A key transition occurred during the Late Cretaceous and Paleogene from the narrow, silled basins that characterized the early North Atlantic to the deep marine connections of the modern Atlantic. The tectonic and oceanographic transition for the North Atlantic was accompanied by a suite of other remarkable events including some of the warmest global climates known for the past 100 m.y., several large body impact events (accompanied by one of the five largest mass extinctions of the past 500 m.y.), and profound changes in carbon cycling and greenhouse gas concentrations associated with mid-Cretaceous black shale deposition and the Paleocene/Eocene boundary. Ocean Drilling Program (ODP) Leg 171B was designed to recover expanded records of this transition period in North Atlantic evolution for examination of the oceanographic, climatologic, and evolutionary history of the Paleogene and Cretaceous ocean. This *Scientific Results* volume, in addition to a Special Publication of the Geological Society of London (Kroon et al., 2001) and other publications referenced here, reports the principle scientific results of drilling during ODP Leg 171B.

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RATIONALE

ODP Leg 171B was designed to recover (1) shallowly buried sediments of great age that could be used for geochemical and evolutionary studies of the Paleogene and Cretaceous ocean, (2) the same sequence of strata along a depth transect to reconstruct the vertical structure of the ocean, and (3) sequences through a series of critical boundaries—intervals associated with major biotic and climatological events in Earth's past (Norris, Kroon, Klaus, et al., 1998). The cruise was originally proposed as a full leg in which there would be time to drill multiple overlapping holes at each site and completely recover the stratigraphic section at each site. Previous drilling with Paleogene and Cretaceous objectives rarely included attempts to splice the recovered sequences in two or more holes to obtain a composite record of the original sequence of strata.

In the end, drilling time was reduced to a 6-week "half leg," which required that plans to splice the Cretaceous sequences in multiple drill holes were largely abandoned. Nonetheless, multiple coring of the Paleogene and the Cretaceous/Paleogene boundary succeeded in recovering expanded sequences of Cretaceous and Paleogene carbonate and siliceous oozes and soft chalk. Drilling also succeeded in recovering numerous sediments that mark critical boundaries, such as black shale events in the Albian, Cenomanian and Turonian, the Cretaceous/Paleogene boundary impact horizon, the Paleocene/Eocene boundary, and the late Eocene impact horizon (Norris, Kroon, Klaus, et al., 1998; Kroon et al., 1998, 1999). Correlative sequences were also recovered in several sites at different water depths, making it possible to study the vertical structure of the ancient oceans during several of these critical boundaries.

OCEANIC ANOXIC EVENT 1B (~120 MA)

The oldest sediments recovered during Leg 171B were lower Albian and upper Aptian calcareous claystone and chalk containing a prominent ~40-cm-thick band of organic shale (Barker et al., 2001). Planktonic foraminifer biostratigraphic correlation suggests that the black shale horizon correlates with a series of marine sapropels deposited during Oceanic Anoxic Event (OAE) 1b in Tethys (Bellier et al., Chap. 3, this volume). Investigations of benthic foraminifer assemblages (Erbacher et al., 1999; Holburn and Kuhnt, 2001; Holbourn et al., in press) and stable isotope stratigraphy (Erbacher et al., 2001) suggest that the black shale recovered on Blake Nose represents a sapropel analogous to those formed during the Pliocene–Pleistocene in the Mediterranean Sea. Stable isotope data suggest that the black shale formed when the overlying water column became well stratified, perhaps by reduced salinities in the surface waters, and restricted ventilation of the ocean floor (Erbacher et al., 2001). Biomarker studies of organic carbon in the black shale have identified the molecular fingerprints of green sulfur bacteria that thrive where anoxic waters reach into the photic zone (J.S. Sinninghe Damsté, pers. comm., 2000). Cyclostratigraphic studies of OAE 1b on Blake Nose suggest that the black shale deposition occurred over ~46 k.y. (Erbacher et al., 2001).

During the Pliocene–Pleistocene, most sapropels in the Mediterranean basins formed when low-salinity surface waters prevented overturning and deep-water ventilation for periods of a few thousand years.

The OAE 1b sapropel on Blake Nose apparently persisted an order of magnitude longer and did so within a much larger and less restricted basin. The biomarker evidence and organic geochemical studies of the type and maturity of organic carbon suggest that the North Atlantic was anoxic below the surface mixed layer (Barker et al., 2001). Erbacher et al. (2001) have suggested that the OAE 1b black shale represents a "super-sapropel" formed when sills to the North Atlantic shoaled and patterns of continental runoff contributed to salinity stratification throughout the basin. Extreme stratification was maintained in the western North Atlantic for only a fraction of the time that the eastern basins of the North Atlantic and Tethys remained stratified because equivalent sections in the Vacontian Basin of southern France and northern Italy are represented by a succession of black shales.

OCEANIC ANOXIC EVENT 1D (~100 MA) AND CENOMANIAN BLACK SHALES

More than 200 m of black shale and limestone representing the upper Albian and lower Cenomanian was recovered in Hole 1052E during ODP Leg 171B. An equivalent sequence of black shale was drilled in Hole 1050C at paleowater depths of ~1200 m greater than in Hole 1052E (Norris, Kroon, Klaus, et al., 1998). Biostratigraphic and cyclostratigraphic work suggests that the section in Hole 1052E accumulated at rates of ~10 cm/k.y. for much of the late Albian, providing a remarkably expanded record of the onset and development of OAE 1d (Lehmann, 2000; Bellier et al., **Chap. 3,** this volume; Norris et al., 2001a; Wilson and Norris **[N1]**). Equally important, planktonic and benthic foraminifers are very well preserved, frequently with glassy shells and original tabular microstructure (Norris and Wilson, 1998), and are accompanied by ammonites (Lehmann, 2000) and gastropods preserved with primary aragonitic skeletons. The exquisite preservation of foraminifers has allowed some of the first stable isotopic studies of the paleoceanographic development of OAE 1d (Norris and Wilson, 1998; Wilson and Norris **[N1]**).

Norris and Wilson (1998) showed that Albian sea-surface temperatures (SSTs) were warmer than those measured anywhere in the modern oceans. Recently, these results have been confirmed in a more exhaustive study of OAE 1d. Wilson and Norris **[N1]** found that SSTs vary considerably throughout the ~1-m.y. interval leading up to OAE 1d and finally dropped abruptly at the onset of black shale deposition. The thermal gradient through the upper water column remained low throughout the interval of black shale deposition which straddles the Albian/Cenomanian boundary. These data provide some of the first direct evidence for the model of black shale deposition associated with increased overturning in the upper ocean and the expansion of organic carbon deposition under high productivity surface waters. Barker et al. (2001) have shown that the organic carbon associated with OAE 1d is mostly terrestrial in origin at Blake Nose.

The long-term oceanographic record of the Albian and Cenomanian has been discussed by Norris et al. (2001a) using stable isotope data from ODP Sites 1050 and 1052. Reconstructions of SSTs suggest that the Cretaceous greenhouse climate began in the late Albian rather than the late Cenomanian as suggested in previous climate reconstructions. Following organic shale deposition associated with OAE 1d, a second phase of black shale deposition took place during the *Rotalipora reicheli* Biozone followed by another phase of black shale formation at the Cenomanian/Turonian (C/T) boundary. Huber et al. (1999) have shown that the C/T boundary in ODP Hole 1050C is associated with the highest intermediate water temperatures (~17°C at a paleo-water depth of ~2300 m) at any time in the Cretaceous. It is currently unclear whether these high temperatures reflect elevated temperatures at the sites of high-latitude deep-water formation or represent deep thermocline waters filling a temporarily silled North Atlantic near the C/T boundary. However, stable isotope data suggest that these warm intermediate waters were relatively short lived because temperatures tended to fall in the Turonian and remainder of the Late Cretaceous (Norris et al., 2001a).

MAASTRICHTIAN PALEOCEANOGRAPHY AND THE CRETACEOUS/PALEOGENE BOUNDARY

Maastrichtian and uppermost Campanian strata are represented by over 200 m of chalk on the central and western parts of Blake Nose. In Leg 171B Hole 1050C, the chalk displays a prominent color cycle that has been related to the orbital precession cycle by MacLeod and Huber (2001) and MacLeod et al. (in press a). These authors also found that planktonic and benthic foraminifers record the cycle in both their abundance and stable isotope signature, suggesting that the color cycles reflect changes in oceanic production and carbonate deposition. Self-Trail (2001) has correlated these strata to onshore wells to revise the calcareous nannoplankton biostratigraphic zonation of the upper Maastrichtian. Stratigraphic studies of onshore boreholes will permit other studies of onshore-offshore evolution of deposition along the Atlantic coastal plain (Edwards et al., 1999).

The Maastrichtian section on Blake Nose is disturbed, particularly near its base, by pervasive plastic deformation that suggests large-scale gravity sliding of partly consolidated chalk. Klaus et al. (2000) proposed using seismic and coring evidence and that the Maastrichtian sequence was slumped at the Cretaceous/Paleogene boundary in association with the magnitude 13 Richter scale earthquake produced by the Chicxulub impact event. Norris et al. (2000) and Norris and Firth (in press) arrived at a similar conclusion and showed that sediment slumped off the Blake Nose was deposited in an extensive blanket of turbidites covering much of the deep western North Atlantic. ODP and Deep Sea Drilling Project sites on the New Jersey margin, the Bermuda Rise, and the Iberian Abyssal Plain all show evidence of mass wasting associated with the Cretaceous/Paleogene (K/P) boundary (Norris and Firth, in press). Max et al. (1999) used seismic evidence from Blake Nose to suggest that K/P boundary mass wasting may have vented gas hydrate reservoirs along the North Atlantic margin and added to the ecological catastrophe produced by the impact event.

The impact ejecta blanket was recovered in three holes at ODP Site 1049 (Klaus et al., 2000). Geochemical studies of the ejecta have confirmed that its chemistry is consistent with an origin as tektites that have been subsequently altered to clay minerals (Speed and Kroon, Chap. 4, this volume; Martinez-Ruiz et al., 2001a, 2001b). Smit (1999) showed that the size and composition of tektites in the ODP 1049 ejecta bed are characteristic of proximal ejecta deposits found elsewhere around the Caribbean and North America. The presence of small chips of metamorphic rocks, shallow-water limestone, dolomite, and shocked quartz are also consistent with derivation of the ejecta from the Chicxulub Crater (e.g., Norris et al., 1999). Recently, Norris et al. (1999), MacLeod et al. (in press a) and Huber et al. (in press) have shown that the geochemistry, biostratigraphic distribution, and size distribution of Cretaceous foraminifers found above the ejecta bed suggest that most Cretaceous planktonic foraminifer taxa became extinct during the K/P mass extinction. For example, MacLeod et al. (in press b) found that there is a small but detectable offset in the Sr isotope ratios of Cretaceous planktonic foraminifers and those characteristic of the earliest Danian that suggests that few Cretaceous species survived the boundary.

PALEOCENE PALEOCEANOGRAPHY AND THE PALEOCENE/EOCENE BOUNDARY

The Paleocene/Eocene (P/E) boundary (~55 Ma) records a ~200-k.y. interval of extreme global warming associated with the massive release of greenhouse gases into the ocean and atmosphere (Bains et al., 1999; Dickens 2001). Drilling during ODP Leg 171B recovered an expanded section of siliceous chalk across the P/E boundary at Sites 1050 and 1051 (Norris, Kroon, Klaus, et al., 1998; Norris et al., 2001b; Norris and Röhl, 1999). A notable feature of the entire Paleocene and early Eocene section at both sites was the pervasive cyclicity in sediment color and other physical properties that has made it possible to produce detailed orbital chronologies for the early Paleogene. For example, Röhl et al. (2001) used scanning X-ray fluorescence logs of split cores from Site 1050 to revise the Paleogene time scale and calibrate the durations of magnetochrons independent of models for seafloor spreading. Norris and Röhl (1999) and Röhl et al. (2000) used physical property cycles to estimate the age of the P/E boundary and the duration of the transient warm period associated with it. Modeling studies suggest that the region around Blake Nose should have been particularly sensitive to orbital forcing and may have salinities and seasonal responses to orbital forcing that depart greatly from those observed over the Atlantic as a whole (Sloan and Huber, 2001).

Results from studies of Site 1051 have contributed to our understanding of the climatology and origins of the P/E boundary event. Katz et al. (1999) presented geochemical data, foraminifer assemblage results, and seismic analysis to suggest that Blake Nose may have contributed greenhouse gases during venting of methane hydrate reservoirs at the P/E boundary. Coring and seismic evidence suggests that if Blake Nose was a gas hydrate reservoir in the Paleocene and early Eocene, the hydrate must have been shallowly seated and could not have contributed large volumes of greenhouse gases during the P/E event (Norris et al., 2001b). Sanfillipo and Blome (2001) demonstrated that there is no major change in radiolarian assemblages or taxonomic diversity associated with the P/E boundary event, in agreement with previous work on planktonic foraminifers. Bains et al. (1999) showed that stable isotope records can be correlated in detail between Site 1051 in the North Atlantic and Leg 113 Site 690 in the Southern Ocean. Together with the cyclostratigaphic chronology of Norris and Röhl (1999) and Röhl et al. (2000) the results of Bains et al. (1999) show that global warming and greenhouse gas outgassing was very abrupt and occurred in several pulses over a total of ~50 k.y. Recently, Bains et al. (2000) found evidence for an increase in export production during the P/E boundary event at several deep-sea sites, including Site 1051. These authors proposed that the increase in carbon sequestration by phytoplankton may have contributed to CO_2 drawdown and the termination of greenhouse warming at the end of the P/E boundary event.

The broad-scale evolution of the Paleocene and Eocene oceans has also been investigated. For example, Faul and Delaney (**Chap. 1,** this volume) have examined the oceanographic history of phosphorus accumulation. They showed that the dramatic rise in $\delta^{13}C$ of marine carbonates during the Paleocene is accompanied by an increase in phosphorus accumulation rates consistent with a large increase in export production leading up to the P/E boundary event. Pletsch (2001) examined the history of palygorskite clay deposition over the same time interval. The widespread prevalence of these clays in North Atlantic sediments during the lower Eocene may reflect the formation and outflow of highly saline deep and intermediate waters from Tethys into the North Atlantic and provide a valuable tracer for the often sought, but rarely found, "warm saline deep water."

EOCENE PALEOCEANOGRAPHY

The middle and upper Eocene on Blake Nose consist of thick sequences of light green and yellow siliceous chalk and ooze that accumulated at 2–6 cm/k.y. There has been considerable pore-water exchange through the sediment pile, but several hiatuses and lithologic breaks act as aquicludes, channeling and distributing the flow of pore waters across Blake Nose (Ussler et al., **Chap. 2,** this volume). Like other parts of the Blake Nose succession, the sediments preserve a well-defined magnetostratigraphy (Ogg and Bardot, **Chap. 9,** this volume) and a clear cyclicity in physical property records that can be used together with the biostratigraphy to create detailed chronologies. Indeed, well-defined biostratigraphies for calcareous nannofossils (Mita, **Chap. 7,** this volume), dinoflagellates (van Mourik and Brinkhuis, **Chap. 6,** this volume; van Mourik et al., 2001) and radiolarians (Sanfilippo and Blome, 2001) are available for correlation to magnetostratigraphic and cyclostratigraphic time scales. Eocene sediments also preserve numerous volcanic ash beds that can be used for intersite correlation on Blake Nose (Pletsch and Reicherter, **Chap. 8,** this volume). Impact ejecta derived from the Chesapeake impact event is present in the upper Eocene sequence at Site 1053 and should in due course provide a well-resolved chronology for that event that can be applied worldwide.

To date, most work on the middle and upper Eocene record has focused on isotope paleoceanography. Wade et al. (2001a; **Chap. 5,** this volume) have shown that there are large amplitude (2‰–2.5‰) shifts in $\delta^{18}O$ of near surface water species within the middle Eocene that suggest large changes in SST or surface-water salinity on precessional and eccentricity time scales. Indeed, development of orbital time scales based on physical property records suggests that the rate and magnitude of paleoceanographic change in the middle Eocene was not all that different from that observed in stable isotope time series from the Pleistocene (e.g., Kroon et al., 2000). Hence, it appears that variability of Eocene SST may have been much larger than has been previously predicted from low temporal resolution analyses of Eocene sediments.

Currently, there are several as yet unfinished studies of Eocene strata drilled during ODP Leg 171B. Norris and Nishi (unpubl. data) are producing a detailed planktonic foraminifer biostratigraphy for the middle and upper Eocene in Sites 1051, 1052, and 1053 that will be tied to the magnetostratigraphy and cyclostratigraphy in these sites. H. Nishi (unpubl. data) has produced faunal counts of planktonic foraminifer assemblages across the middle Eocene/late Eocene boundary to document faunal turnover associated with the extinction of the morozovellid and acarininid planktonic foraminifers. He and his students are extending their faunal work across the late Eocene impact horizon at Site 1053. Smit and Kroon (unpubl. data) are producing the stable isotope record of planktonic foraminifers across the same interval at Site 1053. A long benthic foraminifer time series record has been produced by N. Shackleton (unpubl. data) for the upper Eocene sequence at Site 1052, and future additions to this record will include isotopic analyses of surface-water planktonic foraminifers by B. Wade and P. Wilson.

CONCLUSIONS

Thus far, ODP Leg 171B has had its largest scientific impact in producing some of our most detailed records to date of events associated with Cretaceous black shale events, the North Atlantic history of the Cretaceous–Paleogene impact, and our first detailed chronologies of the Paleocene/Eocene boundary. The drilling leg also proved that it is possible to recover expanded sequences of quite old sediments at shallow burial depth and served to usher in a renewed interest by paleoceanographers in the climatology, evolution and oceanography of past "extreme" climates. Continued work on the middle and upper Eocene strata drilled during Leg 171B will provide fresh insight into the climate variability and chronology of the transitional period between the Eocene greenhouse world and the glaciated Earth of the Oligocene and Neogene.

The JOIDES "extreme" Climates Program Planning Group has recently formulated a rationale for drilling records of past extreme climates. (Kroon et al., 2000b). Many of the phenomena such as those found at Blake Nose can be modeled to test aspects of Earth's climate, the carbon cycle, and marine ecosystems. The geochemical aspects of the transient, large disturbances associated with greenhouse gases can be revealed in sediments, as shown by Blake Nose drilling. It is now of the utmost importance to drill and recover sediments from the same events, which are characterized by large perturbations of the carbon cycle in other parts of the world along depth transects. Documentation of the amplitude and timing of change of these events will increase understanding of the pervasiveness of the events and the processes involved.

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CHAPTER NOTES*

N1. Wilson, P.A., and Norris, R.D., submitted. Stability of tropical warmth and global carbon cycle perturbation during the mid-Cretaceous greenhouse. *Nature.*

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*Dates reflect file corrections or revisions.