CRETACEOUS CLIMATE-OCEAN DYNAMICS:
FUTURE DIRECTIONS FOR IODP

A WORKSHOP SPONSORED BY JOI/USSSP AND NSF

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EXECUTIVE SUMMARY

In recent years, a surge in the amount and quality of paleoclimatic data has renewed interest in Cretaceous climate and ocean dynamics. New data have provided a more precise picture of paleotemperatures and climate variations, and research on Cretaceous climate has entered an exciting, multidisciplinary phase in which geological, geochemical, geophysical and paleontological data can be integrated between marine and terrestrial realms and into modeling studies, with the goal of better constraining the controls on climate change during intervals of overall warmth. In July, 2002, the JOI-USSSP/NSF-sponsored *Workshop on Cretaceous Climate and Ocean Dynamics* held in Florissant, Colorado, brought together a multinational group of more than 90 scientists (including 16 graduate students) with diverse research interests and expertise. The conference objective was to summarize the current state-of-the-art in our understanding of Cretaceous paleoclimate and to discuss future research priorities. Ocean drilling has been crucial in our advances to date and is a critical priority for the future of research in this field.

Ultimately, our interest in Cretaceous climate stems from the current concern over modern global warming. Some of the most important earth science questions of our time relate to understanding how human activities may be modifying current and future climates. Will Earth enter another warm climate state due to rising atmospheric greenhouse gas concentrations? If so, what kinds of biota are likely to adapt/evolve and which face extinction? Will Earth enter a "permanent" El Niño or will the system exhibit variability that allows for periods of increased/decreased marine productivity? These are just a few of the questions for which Cretaceous climate studies may hold the key. For example, many critical questions involve how the biosphere will adapt to global warming. Because sea level was high, there is a rich land-based record for the Cretaceous. This paleontological record serves as an archive of biotic responses to climate change in terms of migration, extinction, adaptation and diversification. Cretaceous research therefore allows us to assess the biotic responses to factors such as warming/cooling, humidity/aridity, and sea level change.

Of all the past warm climate periods, the Cretaceous may be the one most richly described with respect to its terrestrial fossil and marine geochemical records. These sediments therefore present special opportunities for multiple proxy studies and new proxy development, as well as well-integrated model-data comparisons, and multidisciplinary studies to understand how terrestrial and marine environments are coupled on a warmer Earth. We now recognize that Cretaceous climate clearly exhibited change on orbital and sub-orbital frequencies, providing us with the opportunity to examine climate change within a warm world on several time scales. Cretaceous climate data can therefore help to inform the public about both near- and long-term possible effects of anthropogenic climate changes.

Presentations and discussions at the Florissant Workshop also made it clear that the Cretaceous paleoclimate modeling community is uniquely positioned to evaluate the reliability of models used in future climate research when atmospheric conditions differ from the modern, and that Cretaceous research into the effects of Large Igneous Province volcanism may provide the key to better understanding environmental (climatic, biotic) perturbations caused by volcanism.

The workshop participants collectively identified critical needs for future research, many in the area of new data acquisition through ocean drilling. These critical needs and drilling priorities are spelled out in the workshop report that follows and in Appendix 2. The Cretaceous paleoclimate community was highly proactive in the Ocean Drilling Program and will continue to support and contribute to the Integrated Ocean Drilling Program objectives. Numerous opportunities exist within Cretaceous drilling objectives to address the priorities of post-2003 ocean drilling, including the deep biosphere, gas hydrates, extreme climates, internal and external forcing of climate change, rapid environmental change, and large igneous province volcanism.

INTRODUCTION

In recent years, a surge in the amount and quality of paleoclimatic data has renewed interest in Cretaceous climate and ocean dynamics. New data have provided a more precise picture of paleotemperatures and climate variations, and research on Cretaceous climate has entered an exciting, multidisciplinary phase in which geological, geochemical, geophysical and paleontological data can be integrated between marine and terrestrial realms and into modeling studies, with the goal of better constraining the controls on climate change during intervals of overall warmth. In July, 2002, the JOI-USSSP/NSF-sponsored *Workshop on Cretaceous Climate and Ocean Dynamics* held in Florissant, Colorado, brought together a multinational group of scientists with diverse research interests and expertise (Appendix 1). The conference objective was to summarize the current state-of-the-art in our understanding of Cretaceous paleoclimate and to discuss future priorities. Ocean drilling has been crucial in our advances to date and is critical for the future of research in this field.

Social Relevance of Cretaceous Climate Research

Ultimately, our interest in Cretaceous climate stems from the current concern over modern global warming. Extreme warmth in the middle part of the Cretaceous represents one of the best examples of "greenhouse" climate conditions in the geological record (Barron, 1983). Substantial evidence for this warmth includes upper ocean isotopic paleotemperatures of more than 32°C in the tropical Atlantic (Norris et al., 2002; Wilson et al., 2002) and more than 30°C at southern high latitudes (Huber et al., 1995; Bice et al., 2003), bathyal temperatures reaching 20°C in the subtropical North Atlantic (Norris and Wilson, 1998; Fassell and Bralower, 1999; Huber et al., 1999), and fauna intolerant of freezing conditions discovered at 71°N (Tarduno et al., 1998). These data suggest that globally averaged surface temperatures in the mid Cretaceous were more than 10ºC higher than today (Bice and Norris, 2002).

Some of the most important earth science questions of our time relate to understanding how human activities may be modifying current and future climates. Will Earth enter another warm climate state due to rising atmospheric greenhouse gas concentrations? If so, what kinds of biota are likely to adapt/evolve and which face extinction? Will a future warm Earth system exhibit climatic and biotic stability or abrupt change and extreme states? How much above modern values can tropical sea surface temperatures rise? How accurately do climate models predict the effects of increasing greenhouse gas concentrations? Will Earth enter a "permanent" El Niño or will the system exhibit variability that allows for periods of increased/decreased marine productivity? From the standpoint of marine productivity, is upwelling an effective process for the delivery of nutrients from ocean deep waters to the photic zone during a warm climate interval? How do climate extremes and rapid climate fluctuations affect biotic stability? Cretaceous climate studies may be the best key we have to answering these questions.

One of the most critical questions involves how the biosphere will adapt to global warming. Because sea level was high, there is a rich land-based record for the Cretaceous. This paleontological record serves as an archive of biotic responses to climate change in terms of migration, extinction, adaptation and diversification. Cretaceous research allows us to assess the biotic responses to factors such as warming/cooling, humidity/aridity, and sea level change. The Western Interior Seaway is a particularly useful tableau in which these changes played out, providing an accessible, high-resolution record with a large signal to uncertainty ratio. The Seaway and other epicontinental seas also serve as important study areas because the geography of the region approximates the coastal plain-maritime interface that is today so densely populated and exhibits the fastest rate of population increase.

Of all the past warm climate periods, the Cretaceous may be the one most richly described with respect to its terrestrial fossil and marine chemical records. These sediments therefore present a special opportunity to investigate how terrestrial and marine environments are coupled on a warmer Earth. Because Cretaceous climate exhibited change on orbital and sub-precessional frequencies in both terrestrial and marine records, we have the opportunity to examine climate change within a warm world on several time scales. Cretaceous climate data can therefore help to inform the public about both near- and long-term possible effects of anthropogenic climate changes. This perspective is simply not available in modern and historical records. Because of the very different land-sea configuration, the Cretaceous can not serve as a direct analog for a future greenhouse Earth. However, it is clear that Cretaceous sediments may hold the best record with which to improve our understanding of climate variability and biotic responses to change on a warmer Earth.

Challenges in Cretaceous Climate Research

Model-Data Discrepancies in Polar Climates

One of the major challenges facing researchers is that most coupled and uncoupled ocean-atmosphere models underestimate the polar warmth that is indicated by mid Cretaceous fossil and geochemical data, especially for Cenomanian-Turonian time when the latitudinal thermal gradient may have been at its lowest (Bice et al., 2003). This failure suggests deficiencies in our ability to properly interpret the warm climate data record, our understanding of greenhouse climate dynamics, and/or deficiencies in the models. In cases where the latter is true, the immediate lesson relevant to future climate change is that these models--the same ones used in much modern climate research--are dramatically underestimating potential future polar warming. Where different models exhibit different greenhouse gas sensitivities, it is only by comparing these models to paleoclimate data that we can begin to say which extreme in CO_2 sensitivity may be more reasonable than another. The Cretaceous paleoclimate community is therefore uniquely positioned to evaluate the reliability of models used in future climate research when atmospheric conditions differ from the modern.

Change on a Variety of Timescales

While the mid Cretaceous had an extreme warm climate, other times during the Cretaceous, such as the Aptian and Maastrichtian, were characterized by cooler deep water temperatures and possible ice-sheets. The fact that the Cretaceous was not a long interval of stable, unchanging warm climate allows us to investigate climate variability on a variety of timescales. The long term overall warming trend from the Aptian to the mid Cretaceous extreme warmth, followed by an overall cooling trend to the Maastrichtian is the longest timescale variation to be explained. On shorter time scales, considerable effort is devoted to understanding what drove periods of dysoxic and anoxic marine conditions or oceanic anoxic events (OAEs)--

stagnant intervals that corresponded to pulses of extinction and evolution of marine nekton and plankton (e.g., Fischer and Arthur, 1977; Erba, 1994; Bralower et al., 1994). On even shorter timescales, we need to explain dramatic variations in subtropical oceans (Wilson and Norris, 2001) and within black shale sequences that exhibit apparent orbital frequencies.

Large Igneous Provinces

The Cretaceous was a time of unusually high rates of production of oceanic crust both at spreading centers and through the eruption of Large Igneous Provinces (LIPs) (e.g., Larson, 1991; Tarduno et al., 1991; Coffin and Eldholm, 1994) such as Ontong Java and Kerguelen plateaus. LIPs represent exceedingly large ($> 10^5$ km^3) outpourings of predominately basaltic magma. The Ontong Java Plateau, for example, represents more than 50 million km^3 of basaltic magma extruded onto the seafloor to form a 30 km thick plateau encompassing an area equal to one third of the contiguous United States. Events of this magnitude are unknown to human experience, but the consequences must have been dramatic. The release of gases (e.g., CO_2, SO_2, Cl, F, H_2O) from Earth's interior accompanying such great eruptions likely had significant consequences for the composition of the ocean and atmosphere, affected the evolution and extinction of terrestrial and marine biota (Larson, 1991; Larson and Erba, 1999; Tarduno et al., 1998; Kerr, 1998), and may have played a primary role in oceanic anoxic events. Our current understanding of the mechanisms linking volcanic activity, extinction/evolution and OAEs is rudimentary. Recent and future drilling efforts will lead to a firmer understanding of the age and evolution of several LIPs, and a clearer picture of the emplacement mechanism and potential environmental perturbations.

Workshop and Report Structure

At the Florissant workshop, the challenges and questions outlined above formed the basis of plenary sessions and keynote addresses that served as an overview of our current understanding of Cretaceous climate. On the third day of the meeting, the group went into the field to view evidence of Cenomanian-Campanian tectonic-eustatic marine cycles exposed in the Rock Canyon Anticline near Pueblo, Colorado. The final day of the meeting included break-out group discussions designed to identify the critical questions in major research areas and work needed to address these problems.

The following report is organized around six major themes with overviews of remaining questions and avenues for future research:

- Stable isotope evidence for extreme Cretaceous warmth
- Biotic records of global change
- Understanding oceanic anoxic events
- Testing glacioeustasy as a mechanism for Cretaceous sea level variations
- Predictions of Cretaceous climate from numerical models
- Global responses to Large Igneous Province volcanism

A list of workshop participants is provided in Appendix 1. Finally, we provide a list of drilling targets (Appendix 2) that will help achieve these goals.

Where sources are cited with no publication year given, the reference is to a workshop abstract, available on the World Wide Web through http://www.whoi.edu/ccod/. This link leads to a community website, which continues to be updated in order to facilitate communication among the Cretaceous research community regarding meetings and future drilling.

THE STABLE ISOTOPE EVIDENCE
FOR EXTREME CRETACEOUS WARMTH

New data and new proxies support the idea of a mid-Cretaceous "hyperthermal" interval with tropical upper ocean temperatures that were several degrees higher than modern values. Coincident with super warm tropical conditions, the Turonian high latitudes may have had temperatures like the modern tropics.

In the past several years, compelling evidence has been presented for tropical and mid- to high latitude temperatures much higher than the modern. Exquisitely preserved foraminifera (those that exhibit "glassy" preservation) from the Cenomanian and Turonian on Demerara Rise in the western tropical Atlantic (Figure 1) yield the warmest tropical sea-surface temperatures (SSTs) yet reported for the entire Cretaceous-Cenozoic. Norris et al. (2002) presented end Cenomanian $\delta^{18}O$ values as light as –4.1‰ (PDB) from tropical DSDP Site 144 planktonics with glassy preservation. Assuming a reasonable range of possible local water $\delta^{18}O$ values, the foraminifera suggest upper ocean temperatures in the range 31-34°C, several degrees higher than the highest modern tropical open ocean temperatures. Subsequently, Wilson et al. (2002) found even more depleted planktonic foraminiferal $\delta^{18}O$, indicating even warmer ocean temperatures, in Site 144 Turonian samples. A potential new biomarker-based paleotemperature proxy suggests that temperatures in the eastern tropical Atlantic through the broad Cenomanian-Turonian were 33.5-35.5°C (Schouten et al., 2003). These findings support the hypothesized "Cretaceous greenhouse" and strengthen the case for a Turonian Cretaceous thermal maximum.

There is also compelling evidence for very warm high latitudes in the mid Cretaceous. A Turonian to Coniacian (~92 to 86 Ma) vertebrate assemblage from a site at ~71˚N paleolatitude has been interpreted as consistent with an Arctic climate with mean annual temperatures exceeding 14˚C (Tarduno et al., 1998). Evidence of Cretaceous tropics that were warmer than modern prompted Bice et al. (2003) to re-examine material used to estimate contemporaneous high-latitude ocean temperatures from DSDP Site 511, at 60ºS on Falkland Plateau (Huber et al., 1995). In the absence of a pronounced regional perturbation from the Cretaceous sea water $\delta^{18}O$ expected at these latitudes (estimated to be –1.5 ‰ SMOW), oxygen isotope ratios from planktonic foraminiferal calcite at Site 511 are indicative of extreme high latitude warmth during the Turonian, with upper ocean temperatures up to 32°C. Textural observations, interspecific isotopic offsets, pore water chemistry, and burial history all argue against a diagenetic explanation for these data. Salinities as low as 27 psu are required to explain the data as a result of freshwater input, but such brackish conditions are inconsistent with the microfossil assemblages. Such extreme warmth at 60° latitude, where summer sea surface temperatures today reach only 3-10°C, is difficult to explain in the absence of extreme greenhouse forcing (pCO_2, 4500 ppmv or greater; Bice and Norris, 2003).

The possible occurrence of a Turonian Cretaceous thermal maximum caused by high atmospheric CO_2 concentrations highlights a ~20 m.y. mismatch between peak inferred tectonic CO_2 production (Larson, 1991) and peaks in Cretaceous-Cenozoic global warmth, sea level, and atmospheric pCO_2 reconstructed from a variety of techniques (Bice and Norris, 2002). This mismatch most likely represents either an artefact of an as yet unidentified Turonian pulse in global ocean-crust cycling, or the influence of other factors, such as $CaCO_3$ subduction (Wilson et al., 2002).

The notion of cooler-than-modern tropics in the Cretaceous (D'Hondt and Arthur, 1996) has seen decreased support in recent years as a result of several lines of evidence. First, oxygen isotope values from very well-preserved, clay-hosted foraminifera (such as those at DSDP Site 144) are now shown to be, with few exceptions, more depleted than those from coeval chalk-hosted specimens (Norris et al., Figure 2). This provides compelling support for the theory that even small amounts of seafloor diagenesis of planktonic foraminiferal calcite can bias paleotemperature reconstructions toward values that are too cool, and that this problem is most pronounced at low latitudes and in regions of low sedimentation rate (Milliman, 1963; Pearson et al., 2001). Pore water flow occurs more readily through carbonates with low clay content (e.g., chalks), allowing for greater opportunities for carbonate dissolution/reprecipitation at and below the seafloor. Second, there is a growing awareness of the likelihood that, in areas of active upper ocean divergence, planktonic foraminifera will record temperatures several degrees lower than actual sea surface temperatures. In coarse resolution ocean models with temperatures that closely approximate mid-Cretaceous estimates, for example, vertical temperature gradients in the upper 50 m can be 2-6°C in upwelling regions, but are less than 1°C elsewhere (Bice and Norris, 2002). Cretaceous planktonic carbonate that was not precipitated in the uppermost few meters of the water column, even pristine original carbonate, is likely to have equilibrium temperatures several degrees less than actual sea surface temperatures.

Critical Needs

Workshop participants identified several critical needs in the areas of $\delta^{18}O$ paleothermometry. These needs are relevant not only to the stable isotope evidence of extreme warmth, but to the proper interpretation of sedimentary stable isotope records in general.

- To fully evaluate the roles played by taphonomy, palaeoecology and non-equilibrium behaviour in Cretaceous palaeothermometry.
- To increase geographic resolution of our records and thereby define inter- and intrabasinal differences in heat distribution
- To increase the stratigraphic resolution of records and thereby better assess the issue of the variability in past warm climates
- To determine the full magnitude of high-latitude warmth during peak greenhouse forcing
- To support new temperature proxy development and encourage multi-proxy studies
- To further examine the issue of global seawater $\delta^{18}O$ in the context of sensitivity to short-term changes in continental ice volume and long-term changes in hydrothermal weathering regimes

Confidence in our reconstructions of Cretaceous greenhouse climatology is ultimately limited by available sediment records. Drilling, especially to obtain high quality, globally distributed depth transects, is vital to our continued progress. Because of the strong sensitivity of polar regions to changes in greenhouse gases and the influence that equator-to-pole temperature gradients have on winds and ocean productivity, the community recognizes a real need for more high latitude marine records. The Atlantic sector of the Southern Ocean is known to hold an intriguing, high quality Cretaceous sequence, which was sampled only sparingly by Deep Sea Drilling Program Leg 71. There is good motivation to return to Falkland Plateau and to attempt to locate similar quality records outside the Atlantic basin region.

BIOTIC RECORDS OF GLOBAL CHANGE DURING THE CRETACEOUS

The patterns of how life responds to the Earth's changing environments can provide important insights into the processes and rates of global change. Biotic records provide independent and complementary proxies to geochemical tools. The opening and closing of oceanic gateways, climate fluctuations due to greenhouse gases, the creation of vast epicontinental seas, and changes in the partitioning of nutrients between land, surface ocean and deep ocean created new opportunities for many groups of organisms while inducing stressful conditions for others.

At various times during the Cretaceous, warming led to increased weathering of the continents and greater delivery and availability of nutrients in the marine realm. Moreover, the production of vast carbonate deposits, particularly in the Late Cretaceous, may have had important feedbacks on global. Changes in the geochemical balance of the oceans and atmosphere had a profound effect on the rates of productivity among the oceanic plankton and benthos, and strongly controlled their patterns of diversity, abundance, and geographic distribution. Studies of calcareous nannofossil, planktonic and benthic foraminifer, and radiolarian assemblages from a variety of marine environments are critical to understanding when and how such perturbations in the Earth system affect the marine biosphere.

Since the Late Triassic, when the calcareous nannoplankton evolved and initiated a major shift in the focus of carbonate deposition from the shelves to the deep oceans, these diverse and abundant groups of unicellular, planktonic marine algae have been intimately linked to global change. The modern distribution of certain sensitive nannoplankton taxa mirrors discrete water-masses, the existence of which is a function of ocean circulation and climate. Thus, global climate exerts, and must have exerted in the past, a major influence over calcareous nannoplankton, as well as other marine calcareous micro-organisms.

Several examples of this control have been documented in the Cretaceous. Using quantitative analyses of calcareous nannofloras and geochemistry, Erba et al. (2004) have shown that a major calcareous nannoplankton group, the nannoconids, experienced a sharp decline across a globally documented positive carbon isotope excursion in the Berrisian-Hauterivian in northern Italy. The nannofossil assemblages of the late Valanginian indicate higher fertility conditions, further supported by the decline in the oligotrophic nannoconids. Rising Sr/Ca ratios in the upper Valanginian carbonates also supports the interpretation of enhanced productivity. This increase slightly leads the carbon isotope excursion, and is coeval with the onset of the nannoconid decline. Volcanism connected with the emplacement of the Paranà Plateau and a "pulse" of seafloor production have been implicated as possible causes (Erba et al., 2004). These volcanic and tectonic events would have increased CO_2 levels in the atmosphere, favoring a climate that accelerated transfer of nutrients from the continents to the oceans, in turn increasing the fertility of surface waters.

Large Igneous Province eruptions, an extreme type of igneous event, are also linked to at least two global Oceanic Anoxic Events (OAEs). Emplacement of Ontong Java and Manihiki Plateaus correlates with OAE1a (late early Aptian), and the eruption of Caribbean and Broken Ridge Large Igneous Provinces correlates with OAE2 (latest Cenomanian). High-resolution nannofossil stratigraphy (Erba and Tremolada, 2004) indicates that these and possibly other OAEs may have resulted from high productivity episodes caused by high concentrations of dissolved and particulate biolimiting metals in the oceans during submarine eruptions (Figure 3).

Premoli Silva et al. (1999) demonstrated that planktonic foraminifera began to diversify during the early Valanginian and persisted as relatively small-sized, low diversity assemblages through most of the Hauterivian. A remarkable increase both in abundance and number of planktonic species and genera, accompanied by an overall increase in size and ornamentation, began in the earliest Barremian and continued through the early Aptian. While they found no major extinction in planktonic foraminifera coinciding with early Aptian OAE1a, Premoli Silva and colleagues suggested that this event represents a temporary paleoenvironmental perturbation characterized in the upper water column by alternating oxygen levels as delimited by fluctuating dominance of different morphogroups of planktonic foraminifera. The effects of the OAE1a perturbation of planktonic foraminifera appear to have terminated only about one million years after the event.

Leckie et al. (2002) documented the evolutionary patterns of calcareous plankton (planktic foraminifera and calcareous nannoplankton) during the mid-Cretaceous (Barremian-Turonian stages, ~124-90 Ma). When combined with the radiolarian record through the same interval (Erbacher et al., 1996), there is compelling evidence that the highest rates of evolutionary turnover (speciation plus extinction) occur at or near the major

Oceanic Anoxic Events. These episodes of widespread organic carbon burial occur in four main intervals (see "Understanding Oceanic Anoxic Events"). Strontium isotopic evidence suggests a possible link between OAEs and rapid oceanic plateau formation and/or increased rates of ocean crust production (Bralower et al., 1997; Jones and Jenkyns, 2001). The association of plankton turnover and carbon isotopic excursions with each of the major OAEs suggests widespread changes in the ocean-climate system (Figure 4). Leckie et al. (2002) concluded that plankton evolution was tectonically-forced, particularly by increased submarine volcanism and hydrothermal activity, due to influences on climate, ocean chemistry, nutrient availability, ocean circulation, and water column structure.

From Cretaceous studies, we recognize that diversity, taxonomic composition and preservation potential of benthic foraminiferal assemblages at shelf localities are strongly influenced by changes in water depth, particularly at times of major sea level change. Thus, most of the observed benthic faunal changes at shelf sites reflect environmental change and taphonomic bias, rather than true extinction and radiation events. Holbourn and Kuhnt examined records of well preserved benthic foraminiferal assemblages across OAE1a, OAE1b, OAE1c and OAE2 from North Atlantic bathyal and abyssal DSDP/ODP Sites and from bathyal to neritic onshore sections in Morocco, Spain, southeast France and northern Germany (Figure 5). They found no evidence for benthic foraminiferal turnover during the OAEs at middle and upper bathyal sites; most taxa recorded at these locations have stratigraphic ranges extending across oceanic anoxic events. Observed changes in biofacies across the OAEs coincide with changes in hydrography and sedimentological facies. Abyssal benthic foraminifers underwent a marked radiation after the latest Cenomanian OAE2 in the Atlantic Ocean and the Mediterranean Tethys, which may have been triggered by a general change towards better oxygenated deep-water.

Critical Needs

Based on data obtained from continental records and ocean drilling, considerable progress has been made in the last two decades toward describing and explaining Cretaceous biosphere changes. However, important unsolved problems remain in our understanding of the ocean-climate system and its impact on the biosphere.

- How is widespread marine biological productivity sustained for 10^4-10^5 years?

- How important was 400 kyr and 100 kyr cyclicity in controlling sedimentary and biotic patterns?
- Did metals or other trace elements play a primary major role in the Oceanic Anoxic Events of the Early Cretaceous and mid-Cretaceous?
- What role did global warming and cooling play in controlling the availability of nutrients, burial of organic matter, water mass production, and biotic evolution during the mid-Cretaceous?
- What is the relative importance of upwelling vs. continental runoff as a nutrient supply mechanism and might this relationship vary across different climate events in a warm world?
- What were the rates of climate change during the OAEs and how quickly did the plankton and benthos respond to those changes?

The rich Cretaceous terrestrial record, increasingly well-characterized marine records, and an increasing number of proxies and model approaches will allow us to better understand terrestrial and marine responses to internal and external climate change. Terrestrial and marine records need to be better integrated using transects across the land-sea transition zones. At the Florissant workshop, lacustrine deposits were identified as an under-utilized source of Cretaceous climate information. The increasing use of organic biomarkers for molecular "fingerprinting" should yield important information about community makeup and environments. Given the vast amount of hydrocarbons sourced from Cretaceous sediments, the portion of our community applying biogeochemical approaches might especially benefit from greater collaboration with the petroleum industry.

UNDERSTANDING OCEANIC ANOXIC EVENTS

Isotope and elemental studies have rejuvenated efforts to understand the causes of Cretaceous oceanic anoxic events (OAEs). Studies using organic matter nitrogen abundance and isotope ratios are providing new insights into productivity and anoxia during OAEs. Carbon isotope ratios show promise as a correlation tool within black shale sequences across terrestrial and marine sequences. The growing body of high quality data, including high resolution platform carbonate records, is providing a more detailed picture of carbon cycle and climate changes through OAEs.

The discovery of black carbon-rich shales in deep-sea drilling sites from the Atlantic, Indian and Pacific Oceans (from DSDP Leg 1 onwards) led in the mid-1970s to the concept of Oceanic Anoxic Events. These episodes occur in the early Aptian (~120.5 Ma; OAE1a), across the Aptian/Albian boundary (~113-109 Ma; OAE1b), in the early Late Albian (~101 Ma; OAE1c), in the latest Albian (~99.5 Ma; OAE1d), across the Cenomanian/Turonian boundary (~93.5 Ma; OAE2), and in the Coniacian-Santonian (~86-85 Ma; OAE3). Such events, whatever their exact nature and cause, were hypothesized to explain deposition of coeval carbon-rich sediments across environments ranging from deep oceans to shelf seas. The original concept was primarily stratigraphic in nature, being based on the assumption that the world ocean underwent a fundamental chemical and/or biological change during such events. Enhanced productivity of organic-walled microfossils and bacteria and/or enhanced preservation of organic matter were both suggested as likely causes.

Among the many black-shale horizons identified on land and in the oceans, the Selli Event (OAE1a) and Bonarelli Event (OAE2) have proven to be of global distribution. Both are recorded, for example, on submarine plateaus in the Pacific Ocean. In 2002, the black shale of the Selli Event was drilled on Shatsky Rise during ODP Leg 198. This extremely carbon-rich horizon (~35% TOC) contains biomarkers for cyanobacteria that could have utilized atmospheric elemental dinitrogen if nitrate levels in the photic zone became vanishingly low because of utilization by plankton (Brassell). This discovery points to upwelling and high productivity as a major forcing of OAE1a.

Nitrogen-isotope ($\delta^{15}N$) data from Cenomanian/Turonian OAE2 black shales from Italy and Morocco are also consistent with sedimentation below a water column that had undergone denitrification (Jenkyns and Tsikos), as is the case today in zones of vigorous upwelling, intense oxygen minima and high fluxes of planktonic carbon to the sea floor. It has been suggested that during at least some OAEs, expansion of the oxygen minimum zone upwards enhanced recycling of phosporus in the photic zone, allowing nitrogen fixing organisms to flourish (Meyers). During OAE2, as in OAE1a, nitrifying cyanobacteria dominated, which, through photosynthesis, produce organic matter having a $\delta^{15}N$ value close to atmospheric nitrogen (0‰).

During the Aptian/Albian Paquier Event (OAE1b), however, nitrifying Archaea, which exhibit large isotopic fractionation at high N concentrations, are the dominant source of the organic matter (Kuypers et al., 2002). Increases in the abundance of Archaea therefore also produces strongly depleted $\delta^{13}N$ values in the OAE organic matter, resembling the $\delta^{13}N$ signature of sediments formed under OAE1a and OAE2 cyanobacteria-rich waters. High C:N ratios are another common characteristic of sediments from these three events, the result of preferential degradation of nitrogen compounds in expanded suboxic environments during anoxia.

In contrast to the early Aptian and Cenomanian/Turonian events, however, OAE1b was a more local event, being confined, as far as we know at present, to the North Atlantic and Tethyan basins. From a study of isotopes and palynology from three sections in the Central Atlantic and western Tethys, Erbacher and Herrle conclude that OAE1b falls into an extremely warm and humid phase of an eccentricity cycle (Figure 6) but that climate change forced by precession (monsoon-driven fertility change) and obliquity (temperature change) are also present in the sequence within which OAE1b occurs (Herrle et al., 2003). This event was probably a factor of 10 times shorter in duration than was OAE2. OAE3 (Coniacian-Santonian) also appears to be a local event (Wagner et al.) with a record dominantly deriving from the Atlantic.

Recent carbon isotope ($\delta^{13}C$) studies from England, Japan, Italy, Morocco and elsewhere now demonstrate that both the Aptian and the Cenomanian/Turonian black shales are associated with a positive carbon isotope excursion (related to excess global carbon burial) in marine pelagic and shallow-water carbonate, marine organic matter and terrestrial higher-plant material (Jahren; Heimhofer et al.; Hasegawa, 2003). Examining the Cenomanian-Turonian OAE2 in platform carbonates of southern Mexico, however, Elrick and Molina showed an abrupt -3‰ excursion in $\delta^{13}C$ that immediately preceded a more gradual 3-4‰ positive that is consistently expressed in multiple sections. The higher sedimentation rates of platform carbonates permits previously unattainable high-resolution records illustrating the relationship between geochemical and physical processes occurring in pelagic and/or hemipelagic systems and those occurring in onshore, benthic-dominated systems.

The Aptian event is also associated with a pronounced negative carbon-isotope excursion, recently interpreted as due to dissociation of methane hydrates (Jahren). A similar excursion has been found in Atlantic and Tethyan sections predating the Paquier Event (Gröcke). Because these characteristic carbon-isotope excursions, both positive and negative, can be found in deep marine, platform and non-marine facies, they offer a novel means of correlation between sediments deposited in the oceans and on the continents. Palaeoclimatic data from continental interiors may now be integrated with the wealth of data from deep-sea drill cores to produce a potentially global view of climate change during critical events in Earth history. For example, Ludvigson et al. have used $\delta^{13}C$ chemostratigraphy to correlate lacustrine carbonates with the marine Aptian-Albian sections. Systematic differences in $\delta^{13}C$ (~1.5‰) between the sections studied may be related to floral responses to moisture stress in the site immediately leeward of the Sevier mountains. $\delta^{18}O$ curves for the two study sites diverge for the time interval corresponding to OAE1b, which has been interpreted as resulting from a local intensification of aridity coincident with oceanic anoxia.

High resolution isotope studies are yielding new insights into the nature of the OAE carbon sinks and timing of events. The stratigraphic position of the most carbon-rich portions of some OAE sequences is not fixed with respect to the carbon-isotope curve: in some localities the onset of the positive excursion coincides with the beginning of black-shale deposition, in others it does not. This mismatch is seen, for example, with OAE2 in the Western Interior (Sageman and Meyers) where organic carbon accumulation rates appear to have increased after the carbon isotope excursion. In Italy, however, the carbon isotope excursion begins abruptly at the base of the Bonarelli sequence itself. Hence, at this high resolution, the "stratigraphic" concept of the Oceanic Anoxic Event breaks down. The mismatch in timing suggests either that some unrecognized effects on local carbon $\delta^{13}C$ (paleoecology, diagenesis and local carbon cycling) obscure the global chemostratigraphic signal, or that the most significant carbon sinks during some OAEs have yet to be identified. In the case of OAE2, there is some evidence that a major locus of organic-matter deposition was the proto-South Atlantic (Forster et al.).

Perhaps one of the most intriguing new results in the study of oceanic anoxic events is evidence of a possible causality between volcanism, primarily large igneous province volcanism, and OAEs. A separate chapter in this report is devoted to the topic of large igneous provinces (see "Global Responses to Large Igneous Province Volcanism").

Critical Needs

Future research on OAEs must continue to characterize the environmental conditions that led to the deposition of organic-rich sediments. Proxies that can provide direct information on nutrients in surface waters, atmospheric CO_2 levels, and the original composition of biotic populations, from microbes to invertebrates, are needed. Multidisciplinary investigations must focus on events that perturbed the global ocean, such as the early Aptian and late Cenomanian OAEs, as well as those that appear to be more regional in scale. There are a number of important questions related to OAEs that can best be addressed through ocean drilling:

- What is the geographic and oceanographic distribution of these events?
- What controls the spatial distribution of anoxia and the rates of change (climatic, chemical, biological) during the event?
- Would a chemostratigraphic definition be more useful than the traditional stratigraphic concept of an OAE?
- What preconditioning (tectonic, climatic, orbital) determined the time scales of the different OAEs and sustained them?
- What is the exact relationship, if any, between OAEs and negative carbon-isotope excursions? Is there a role for methane?
- Did metals or other trace elements play a major role in the anoxic events?
- What is the relationship between OAEs, ocean temperature changes and links to sea level?
- What is the impact on the carbon cycle and its budgets, reservoirs and fluxes through the various OAEs?
- What is the expression of these events on the continents (e.g. in lakes) versus shelf areas and the deep ocean?
- Is there a causal relationship between large igneous province volcanism and OAEs?

To address many of these questions in a rigorous fashion will require sections with a broader geographic distribution than those currently available. Efforts must be made to identify records of OAE in expanded, immature sections that will allow high-resolution studies at a millennial scale. Drilling priorities include the high latitudes (especially Arctic) transects from continent to the deep.

TESTING THE GLACIOEUSTASY HYPOTHESIS AS A MECHANISM FOR CRETACEOUS SEA LEVEL VARIATION

Scientific ocean drilling provides an opportunity to resolve the record of global (eustatic) sea level change through the study of sediments from carbonate platforms, atolls, passive continental margins and the deep-sea. With advances in ocean drilling technology, methods of dating and correlating sedimentary sequences, and geochemical techniques for reconstructing paleotemperature history, there is great potential for improvements in the accuracy of Cretaceous global sea level curves and in understanding when and how Cretaceous climate was influenced by, or responsible for, global sea level variations.

One of the long-standing controversies about mid- to Late Cretaceous climate regards how large (>20-30 m), rapid (<100 kyr) sea level variations could have occurred globally during a greenhouse climate that is assumed to have been ice sheet-free, since the only known cause for such eustatic variations is the growth and decay of continental-scale polar ice sheets. Reconciliation of this paradox requires demonstration, first, that short-term transgressive and regressive events were globally synchronous and similar in magnitude and, second, that these events coincide with geochemical indicators consistent with changes in continental ice volume. Sedimentologic indicators of polar ice, such as glacial diamictites and glendonites, are also desirable. To date, however, these are known only in early Aptian and older Cretaceous sediments in southern Australia and the high Arctic (Frakes et al., 1992) and are, in some cases, equivocal.

Correlation of synchronous deep-water benthic and low-latitude mixed layer planktonic foraminifer δ^{18}O increases and a major sequence boundary recognized provides compelling evidence for growth of a moderate sized ice sheet during the early Maastrichtian, sometime between 69.2 and 71.2 Ma (Miller et al., 1999). Support for this interpretation comes from the relatively enriched δ^{18}O values of deep sea benthic and high latitude planktonic foraminifera, which equal or exceed 1‰ during the early Maastrichtian (Barrera and Savin, 1999) (Figure 7). Subsequently, Miller et al. (2003) argued for growth of small, ephemeral ice sheets to explain correlation between middle Cenomanian and middle Turonian sequence boundaries and deep water benthic oxygen isotope increases.

Gale et al. (2002) also contend that glacioeustacy occurred during the Cenomanian. These authors identified six mid- and late Cenomanian sea level cycles with frequencies of 400 kyr that can be correlated from the coastal plain of SE India to 11 individual sections in northwest Europe. Analysis of facies shifts and fluvial incision indicates that rapid falls of sea level took place at the sequence boundaries, with down-cutting of 10-25 m. These are minimum values, depending on the quality and extent of outcrop. The major falls (mid-Cenomanian, *C. inerme* Zone, and late Cenomanian, *M. geslinianum* Zone) are coincident with positive δ^{18}O events of up to 2 to 2.5‰ in NW European chalk successions. They correspond with the southerly migration of Boreal nektic and benthic taxa in NW Europe, as well as rapid increases in brachiopod and belemnite δ^{18}O values and positive δ^{13}C shifts (Voigt, 2000).

The mid-Cenomanian eustatic and isotopic events recognized by Gale et al. (2002) and Voigt (2000) may correspond to a 1‰ positive δ^{18}O shift recorded by deep sea benthic foraminifera at ODP Site 1050 (Figure 7). However, there is no evidence of a similar δ^{18}O shift in the late Cenomanian record at Site 1050 or at southern high latitudes. Correspondence of the mid-Turonian "glacioeustacy" event of Miller et al. (2003) with highly depleted deep sea benthic and southern high latitude δ^{18}O values suggests that glacioeustasy at this time was unlikely (Huber et al., 2002).

Analyses of a number of δ^{13}C records from Cretaceous pelagic sediments reveal widespread, synchronous shifts that are attributed to changes in the relative burial fluxes of organic carbon and carbonate carbon resulting from variations in sea level. This proposed relationship is supported by comparison of Campanian carbon stable isotope and sedimentologic profiles from Tunisia, France, England, Germany and Kazakhstan, which all show remarkably similar patterns. Positive δ^{13}C excursions ranging from +0.2 to +0.3‰ are recorded across the Santonian/Campanian boundary (~83.7 Ma) and in the mid-Campanian (~78.7 Ma), and a negative δ^{13}C excursion of -0.4‰ in the upper Campanian (~74.8 Ma) with durations of 600 - 750 kyr (Jarvis et al., 2000). The long-term carbon isotope trend in the Campanian pelagic sections broadly follows first-order eustatic sea level with relatively stable and high δ^{13}C values in the lower Campanian reflecting stable, high eustatic sea level, with decreasing δ^{13}C values in the upper Campanian reflecting falling eustatic sea levels (Figure 8).

The importance of accurate stratigraphy to correlating third-order sea level cycles is demonstrated by comparison of radiometrically interpolated and biostratigraphically correlated versions of the Haq et al. (1987) sea level curve with the sea level curve developed by Hancock (1990) for northwest Europe (Figure 9). Significant mismatch in the relative timing of the transgressive peaks and regressive troughs is caused by differences in the biozonal schemes, stage boundary definitions, and time scales that are used for each curve. Hancock (1993) noted that there is no simple right or wrong answer to how sea level curves should be plotted, but he emphasized that comparison of different sea level curves is only possible if their construction is based on identical stratigraphic criteria.

Critical Needs

Large and rapid changes in Cretaceous sea level that have been recorded during times of global warmth pose a paradoxical problem to geologists and climatologists as they cannot be explained by any other known mechanism but glaciation. In the absence of direct geological evidence, the case for Cretaceous polar ice sheets requires demonstration that proxy signals of sea level and climatic change are globally synchronous and consistent in their magnitude and direction of change.

In order to resolve the Cretaceous ice-sheet debate, field and laboratory data that can be correlated at Milankovitch time scales must be obtained from a global array of sites and depositional settings. The following target intervals are identified as potentially yielding the greatest insight to the question of Cretaceous glacioeustasy: (1) late Maastrichtian (~66.5 Ma); (2) early Maastrichtian (~70.5 Ma); (3) late Campanian (~74.5 Ma); (4) Coniacian-Santonian (~89.0-83.5 Ma); (5) mid-Turonian (~92-91 Ma); (6) Cenomanian/Turonian boundary interval (~94-93 Ma), (7) mid-Cenomanian (~95.5 Ma); and (8) Aptian/Albian boundary interval (~114-112 Ma). Impermeable and low porosity clay-rich sediments from low and high latitudes should be sought to obtain the best preserved and most climatically informative oxygen isotope records across these intervals. More detailed and higher resolution records from continental margin, carbonate platform, and transitional terrestrial-marine environments that have high-resolution (e.g., Milankovitch scale) age control will be essential to reconstructing a reliable Cretaceous eustatic curve.

The critical questions to be resolved involving Cretaceous glacioeustasy and sea level change include:

- What were the magnitudes and rates of Cretaceous sea level changes?
- Do Cretaceous sea level fluctuations demonstrate a Milankovitch frequency? If so, how did Milankovitch cycles affect Cretaceous sea level?
- Which sea level changes can be proven to be globally synchronous?
- Which, if any, Cretaceous sea level changes were glacially forced?
- What is the mechanistic relationship, if any, between sea level rise and OAEs?
- What are the timing, extent and cause of carbonate platform drowning events?

In addition to the many questions related to ice-sheet growth and sea level change, there are Cretaceous sea level change issues that have important relevance to current global warming and environmental problems (such as coral bleaching events). In future drilling and field studies, progress in sea level studies will require that we:

- Identify localities that have minimal regional tectonic influences.
- Locate terrestrial sections that record incisement during marine incursions in order to provide a quantitative estimate of sea level regression.
- Use every environmental proxy available in stratigraphically complete, well-dated sedimentary sequences.
- Accurately correlate between epicontinental and deep-sea records using orbitally-tuned sections, radiometrically-dated horizons and unique global geochemical events.

PREDICTIONS OF CRETACEOUS CLIMATE FROM NUMERICAL MODELS

Through the use of a variety of numerical models, significant progress has been made in defining and understanding the complexities of Cretaceous climate. Old paradigms have been replaced by a variety of new paradigms, some speculative, that will be the focus of the community for the near future. Many of the remaining critical questions in Cretaceous climate science are shared by the future global change community, including the roles of clouds, water vapor, tropical climate, and CO_2 in driving global climate. The Cretaceous community is uniquely positioned to contribute significantly to these questions.

Since the original efforts of Eric Barron and co-workers in the early 1980s, considerable progress has been made towards understanding circulation during the Cretaceous greenhouse world. New paradigms depart significantly from the classic view of the Cretaceous as a monotonous, warm, stable climate forced by moderately high (4-6 x present-day levels) atmospheric carbon dioxide levels and a "halothermal" circulation. At the same time, considerable diversity of opinions remains among Cretaceous paleoceanographers. While not supported by all researchers, there is a growing consensus that warm Cretaceous and early Paleogene oceans can be explained by the sinking of warm high-latitude waters and do not require bottom water formation in low latitudes (Brady et al., 1998; Poulsen et al., 1999; Bice and Marotzke, 2001; 2002). At the Florissant workshop, the following diverse views were expressed:

- In a Cretaceous greenhouse world, the westerly winds developed only seasonally. In the absence of persistent westerlies, the subtropical ocean gyres would have weakened leading to an ocean circulation dominated by eddies and an absence of surface western boundary currents or a focused site of deep water formation. As a result, the pycnocline would have been more diffuse than today, contributing to oceanic heat transport (Hay).
- Temperatures inferred from mid-Cretaceous planktonic isotope data allow for a broad range of carbon dioxide concentrations. Cooler temperatures require ~900 ppm CO_2, while in order to match the warmest tropical paleotemperature estimates, general circulation models of the Cretaceous indicate that atmospheric CO_2 concentrations were perhaps as high as 4500 ppm (Bice et al.).

- With a CO_2 concentration of 1120 ppm, the NCAR Climate System Model predicts deep-ocean temperatures of 9-11°C, and surface temperatures that are 3-4°C and 6-14°C warmer than modern at low and high latitudes, respectively. Ocean heat transports in the model are diminished in the Northern Hemisphere and enhanced in the Southern Hemisphere (Otto-Bliesner et al.).
- High atmospheric pCO_2 levels are not required to achieve a very warm Cretaceous climate. With 1120 ppm CO_2, the Hadley coupled ocean atmosphere model predicts a hot Cretaceous world dominated by latent heat, resulting in high latitude temperatures that are higher than those predicted by the NCAR models and high latitude salinities that are lower. The difference between the Hadley model and other climate models that require higher pCO_2 to achieve the same temperatures is in the parameterization of clouds (Valdes and Markwick).

These views of the Cretaceous general circulation are a sign not only of the progress that has been made in the last 20 years, but also represent the scientific debates that will be played out in the next decade. As an example of the relevance of Cretaceous climate science, many of the topics discussed at the Florissant workshop mirror discussions that are being held regarding future global climate change, including the sensitivity of the climate to pCO_2, the presence or absence of a "tropical thermostat," the role of clouds and water vapor in climate change, and the response of ocean thermohaline circulation to polar warmth and an increased hydrologic cycle.

Another critical issue highlighted in the workshop was the very large difference in the temperature response of general circulation models to Cretaceous boundary conditions. For example, in comparison to the NCAR models (GENESIS and CSM), the Hadley Centre model (HadCM3) contains a much stronger CO_2 sensitivity by way of the cloud. The same spectrum of climate models used in Cretaceous research is being used to predict future climates, but it is only through comparison against the Cretaceous data record that we can begin to quantitatively address the question of whether a model's sensitivity to increased greenhouse gas concentrations is too large or too small. If, for example, the low subpolar salinities predicted by the Hadley Centre model are inconsistent with the existence of abundant and diverse Cretaceous planktonic foraminifera in these latitudes, then there is good reason to suspect that less sensitive models used to predict anthropogenic change may be better estimating future polar temperatures.

However, the inverse may be true: the question hinges on better understanding the plausible salinity tolerances of extinct species. This dilemma highlights the need for an interdisciplinary and multiple-proxy approach to Cretaceous climate research.

Another sign of the maturity of Cretaceous climate science is awareness that the Cretaceous climate displayed considerable variability over its 79 million years. This variability includes changes in the geochemical state of the oceans, long-term climate warming and cooling, and millennial-scale changes in the hydrologic cycle. Possible causes of Cretaceous climate variability include:

- Large, rapid shifts in atmospheric pCO_2. General circulation models indicate that large shifts in pCO2 are required to explain tropical sea-surface temperature variations in the mid-Cretaceous leading into the Cretaceous Thermal Maximum. These pCO_2 large shifts fall within the range of atmospheric CO_2 estimates that have been calculated through proxy methods (Bice and Norris, 2002).
- Orbital forcing. Results from a general circulation model demonstrate that the hydrological cycle in western North America is sensitive to precessional forcing. The formation of bedding couplets is controlled by changes in the rate of mechanical erosion, which is a function of surface runoff (Floegel et al.).
- Paleogeographic changes. Results from a coupled ocean-atmosphere model indicate that the opening of the Atlantic Equatorial Gateway could have caused a large-scale reorganization of the tropical climate, and regional warming. This mechanism was considered as a cause of the Cretaceous Thermal Maximum (Poulsen et al., 2003).

Critical Needs

Numerical models of the Cretaceous climate can provide insights into the working of a greenhouse world and help evaluate the performance of models used to forecast future climate change. However, good Cretaceous simulations require accurate and detailed descriptions of boundary conditions and other critical aspects of the Cretaceous environment. Progress continues to be made in both of these areas and includes the following:

- The production of high-resolution paleotopographic and paleobathymetric elevation models and detailed descriptions of gateway openings and plate movements (Scotese, Lawver and Gahagan).

- The development of detailed global vegetation maps, analysis of areas of agreement and disagreement between different reconstructions, and the use of various regression models of climate and leaf forms (Upchurch et al., Scherer et al.).
- The reconstruction and variability of detailed current systems, such as the middle Cretaceous contour current system along the continental rise of the deep southeastern Gulf of Mexico (Buffler).

The need for detailed data sets to use as boundary conditions and to validate the climate models will only increase as model resolution and sophistication increase. In addition, targeting specific time intervals of interest could facilitate model intercomparison and validation. At the same time, the Cretaceous community recognizes the continuing potential for contributions from experiments using relatively simple models, the need for attention to transient responses in the models as possibly analogous to real climate transitions, and the growing need for the use of models that incorporate biogeochemical and isotopic processes. To facilitate these endeavors, we encourage and support cross-disciplinary collaborations between climate scientists and those who gather Cretaceous climate proxy data.

The study of climate variability in the Cretaceous requires continuous time-series of environmental change. As more continuous, high-resolution (millennial scale) archives are developed, the picture of Cretaceous climate variability will expand. Obtaining these records and identifying the causes of climate variability in a greenhouse world, particularly those that can cause "surprises" such as rapid $p\mathrm{CO}_2$ fluctuations or tropical climate shifts, should be a major focus of the Cretaceous scientific community. The modeling community is in the enviable position of benefiting from ocean drilling and other data acquisition in every part of the globe, if the current trend toward well-integrated model-data comparisons continues.

GLOBAL RESPONSES TO LARGE IGNEOUS PROVINCE VOLCANISM

Perhaps one of the most intriguing new areas of Cretaceous research seeks to understand possible relationships among voluminous igneous events (known as Large Igneous Provinces or LIPs), climate, and episodes of high marine productivity. The search for definitive evidence of causality between LIP volcanism and oceanic anoxic events, which may be induced by high concentrations of dissolved and particulate biolimiting metals in the oceans, requires strategic drilling and close collaboration among stratigraphers, geochemists and marine biologists.

Large Igneous Provinces (LIPs) were constructed during voluminous magmatic events that took place over geologically brief (<3 m.y.) time intervals (e.g., Duncan and Richards, 1991; Tarduno et al., 1991; Coffin and Eldholm, 1994). These events are thought to be associated with massive thermal anomalies in the mantle known as "superplumes" (Larson, 1991). The volume of crust produced by LIPs in the Cretaceous was almost three times greater than in prior and subsequent time periods. In particular, three prominent intervals of LIP eruption occurred: late Barremian (with Ontong Java Plateau (OJP) and Manihiki Plateau construction in the Pacific), late Aptian to early Albian (Kerguelen Plateau in the Indian Ocean), and Cenomanian-Turonian (Caribbean Plateau). In addition, subaerially erupted flood basalts of the Turonian-Coniacian Strand Fiord Formation are part of a large magmatic pulse that may include large parts of Ellesmere Island and the Arctic Ocean basin.

Increased rates of volcanism associated with oceanic plateau formation and sea floor spreading in Cretaceous time probably caused a variety of biological and geochemical responses. A current popular model for the sporadic occurrence of oceanic anoxic events (OAEs) in the Cretaceous ties hydrothermally-induced changes in ocean chemistry to increased surface productivity, followed by mid-to-deep water oxygen depletion and accumulation of organic-rich sediments (e.g., Vogt, 1989; Leckie et al., 2002). In addition, CO_2 outgassing during mid-Cretaceous volcanism may have increased global temperatures (Bice and Norris, 2002). The Strand Formation flood basalts, for example, immediately underlie faunal assemblages consistent with very warm Arctic climates (Tarduno et al.). Caribbean and high latitude North Atlantic volcanism spanning the Turonian are approximately coeval with geochemical evidence for a Turonian Cretaceous thermal maximum (see "Stable Isotope Evidence for Extreme Cretaceous

Warmth"). However, small but possibly significant mismatches between radiometrically dated oceanic basalts and stratigraphically dated geological responses currently make it difficult to establish cause and effect relationships with certainty (Figure 10).

Metal anomalies that arise from hydrothermal activity during ridge-crest and mid-plate volcanism can be advected for significant distances by plumes (e.g., Baker et al., 1994), especially where the water column is reducing. Megaplume activity can enrich Fe, Mn, and trace metals (e.g., Cr, V, Ni, Zn, Cu, Ba) in proximal sediments by several orders of magnitude (Figure 11). This signature in sedimentary sections has great potential for precise stratigraphical correlation between hydrothermal activity and its potential environmental responses, including OAEs and plankton turnover. Preliminary metal data from the Cismon section, for example, appear to record OJP volcanism in strata within and directly below the Selli Level (Turgeon et al.; Duncan and Huard, 1997) providing an enticing causal scenario for OAE1a. Both OAE1a and OAE2 are interpreted as high productivity episodes (see "Biotic Records of Global Change"). High productivity may have been induced by high concentrations of dissolved and particulate biolimiting metals in the oceans and increased CO_2 in the atmosphere during submarine volcanism on Ontong Java and Manihiki Plateaus (OAE1b) and the Caribbean plate (OAE2).

Strontium isotopic evidence also suggests a possible link between OAEs and times of rapid oceanic plateau formation and/or increased rates of ridge crest volcanism (Bralower et al., 1997; Jones and Jenkyns, 2001; Leckie et al., 2002). However, the temporal relationship between LIP formation and OAEs derived from radiometric estimates is not yet straight forward. Radiometrically dated basalts from the OJP and Manihiki Plateau average 123 Ma, while the Selli black shale (OAE1a) and associated isotopic ratio anomalies occurred 2-3 m.y. later. Basalts from the Kerguelen Plateau suggest major volcanic activity, much of which was subaerial, beginning at about 118-119 Ma, which possibly continued at decreased rates and contributed to OAE1b and elevated paleotemperatures in the Albian. Basalts from the Caribbean Plateau, which were previously determined to have radiometric ages of about 88-91 Ma (Sinton and Duncan, 1997), have been redated and, with one exception, now have radiometric ages of about 92-95 Ma (Duncan, unpublished data). Thus, the case is considerably stronger, but not yet certain, that Caribbean Plateau volcanism contributed to OAE2 and associated isotopic anomalies near the Cenomanian/Turonian boundary. These new age ^{40}Ar-^{39}Ar whole rock ages are more precise than previous estimates, but still produce the same estimated duration of volcanic activity of about 3 m.y. Additional improvements in radiometric dating will rely on finding samples from which feldspar can be separated.

Ocean drilling can make a major contribution to investigating the linkage between LIP volcanism and environmental change. High-resolution studies continue to reveal the time scale and nature of biostratigraphic, lithologic and chemical changes at OAEs. An array of drilling sites designed to recover continuous sections for targeted OAEs will document "near-field" and "far-field" effects, trace element abundance patterns, and Cretaceous ocean circulation. Advances in analytical methods (ICP-MS) open the way for detection of a wide range of potentially diagnostic elements from large numbers of samples. Finally, other tracers with short residence times are required to trace hydrothermal activity regionally and globally. Osmium isotope ratios, specifically $^{187}Os/^{188}Os$, are limited to analysis of sediments deposited in oxic conditions, but hold significant potential to meet this goal (Ravizza et al., 2001). For example, based on analyses of metalliferous sediments from Cyprus and Oman, there is an excursion close to the Cenomanian/Turonian boundary that may be associated with LIP emplacement in the Caribbean.

Critical Needs

A large number of questions regarding Cretaceous volcanism have arisen in the past decade.

- Is the timing and duration of LIPs correlative with OAE events? What was the effect of the world-wide, mid-Cretaceous volcanic pulse on the deposition of C_{org}? via improved radiometric dating of LIPs; improved dating of OAEs (GPTS, Os-dating of black shales); sites proximal to an ocean plateau that records both volcanic history and OAE events (e.g., Nauru Basin and OJP). Drilling priorities for OAE1a in the Pacific include Magellan Plateau, Nauru Basin, and seafloor sufficiently young to be above the CCD at OJP time (i.e., M1-M3 age). In the Atlantic and Indian Oceans, the Weddell Sea and Maud Rise are high priorities. For OAE2, future drilling in the Pacific on Magellan Rise, Manihiki Plateau, Hess Rise, and Cenomanian-Turonian atolls is needed.

- Which OAEs are LIP-related and which have other causes? We need high-resolution, multiple-proxy studies of "regional" OAEs, for which no LIP has been identified.
- What was the effect of mid-Cretaceous volcanism on paleotemperature and pCO_2? Needed: updated calculations of ocean heating by massive lava flows in appropriate Cretaceous ocean conditions; high-resolution GCM of Cretaceous ocean with LIP inserted to model altered flow and circulation downstream from LIP effluent; better estimates of degassing and hydrothermal trace element "fingerprints"; understanding of gas hydrate distribution and stability in early and mid-Cretaceous oceans; better information about primary trace metal contents of LIPs and alteration effects; which metals are bio-limiting (or toxic) and which phytoplankton are important in OAEs. Was the volcanic pulse a direct cause of "greenhouse" climate conditions? Or is methane dissociation a more likely trigger?
- Do microplankton and microbenthos respond to the physical, chemical and biological oceanographical changes associated with OAEs? What are the causes of apparent extinction and evolution in these time intervals?
- What are the different effects of predominantly submarine LIPs vs. predominantly subaerial LIPs? High-resolution, multiple-proxy studies of K/T (Deccan) or Valanginian (Parana) vs. early Aptian (OJP) or C/T (Caribbean) events are needed to address this question.

Most of these questions can only be addressed through ocean drilling. A far more comprehensive set of ocean drill sites is required to test the relationship between metal anomalies, OAEs and inputs from sea floor spreading centers and ocean plateaus. For example, transects drilled progressively "downstream" of LIP eruptions will document trace element abundance patterns and should yield information about "near-field" and "far-field" effects of metal inputs and Cretaceous ocean circulation.

Appendix 1. Workshop Participants

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Roger L. Larson	University of Rhode Island
Jiri Laurin	Academy of Sciences of the Czech Republic
Lawrence A. Lawver	University of Texas
R. Mark Leckie	University of Massachusetts
Jackie A. Lees	University College London
Elana Leithold	North Carolina State University
Greg A. Ludvigson	University of Iowa
Kenneth G. MacLeod	University of Missouri
Adam McConnell	University of Massachusetts
Cheryl L. Metz	Texas A&M University
Philip A. Meyers	University of Michigan
Stephen R. Meyers	Northwestern University
Isabel P. Montanez	University of California-Davis
Dragana D. Nebrigic	University of Texas at Dallas
Richard D. Norris	Scripps Institution of Oceanography
David Osleger	University of California-Davis
Bette L. Otto-Bliesner	National Center for Atmospheric Research
Desiree Polyak	University of Massachusetts
Christopher Poulsen	University of Southern California
Lisa M. Pratt	Indiana University
Isabella Premoli Silva	University of Milan
Greg Ravizza	University of Hawaii
Shelley Rios	National Science Foundation
Bradley Sageman	Northwestern University
Sarah Santee	University of California-Davis

Christopher R. Scotese	PALEOMAP Project
Paul J. Sikora	University of Utah
Laura J. Snow	Oregon State University
Erica M. Sterzinar	University of Massachusetts
John A. Tarduno	University of Rochester
Steven C. Turgeon	ICBM - Universität Oldenburg
Garland R. Upchurch	Southwest Texas State University
Paul J. Valdes	University of Reading
Silke Voigt	University of Cologne
Hu Xiumian	Chengdu University of Technology
Thomas Wagner	University of Bremen
David K. Watkins	University of Nebraska
Timothy S. White	Penn State University
Peter Wilf	Penn State University
Paul A.Wilson	University of Southampton
Sherwood W. Wise	Florida State University

Appendix 2. Drilling Target Summary

LOCATION	**PROPOSAL #**	**PROPONENTS**
PACIFIC RISES		
Manihiki Plateau		Roger Larson and Elisabetta Erba
Magellan Rise		Roger Larson and Elisabetta Erba
Hess Rise		Roger Larson and Elisabetta Erba
HIGH LATITUDE SOUTH		
Weddell Sea	503 (full)	Woody Wise, W. Jokat, et al.
Naturaliste Plateau		Darren Gröcke
Agulhas/Crochet Plateaus		Brian Huber
Mozambique/S. Madagascar Ridges		Dick Norris and Karen Bice
Falkland Plateau		Karen Bice, Woody Wise
HIGH LATITUDE NORTH		
Arctic/Lomonosov	533 (full)	Jan Backman
Arctic-Atlantic Gateway	588 (pre)	F. Gradstein, S. Ren, et al.
Hudsons Bay	617 (pre)	Tim White
Bering Sea		Tim Bralower
CONTINENTAL MARGINS		
Carolina Transect	616 (pre)	Tim Bralower, S. Culver, et al.
J-Anomaly Ridge	562 (full)	Dick Norris, Karen Bice, et al.
Cape Verde Basin		Tom Wagner
Brazil Margin		Lisa Pratt, Simon Brassell, Karen Bice
Northwest Australia		Paul Bown, Leon Clarke
NE Japan	608 (pre)	Takashi Hasagawa
OTHER CRETACEOUS OBJECTIVES		
Scott Plateau	513 (full)	B. Opdyke, H. Stagg, G. C. H. Chaproniere
Hikurangi LIP	542 (pre)	N. Mortimer, R. Wood, et al.
Chicxulub Impact Crater	548 (full)	J. Morgan, R. Buffler, et al.
Caribbean LIP	561 (full)	Bob Duncan
S. Rockall-Hatton Plume	596 (pre)	Tim Morrissey, P. Shannon, et al.
Somali Basin	606 (pre)	Hiroshi Nishi, Hisatake Okada, Brian Huber
Ontong Java Plateau	623 (pre)	C. Neal, M. Coffin, et al.

Figure Captions

Figure 1. Scanning electron photomicrograph images of foraminifera from Deep Sea Drilling Program Site 144. All scale bars represent 50 µm. (Norris et al., 2002). These samples are representative of the excellent preservation that has been observed in Cretaceous clay-rich drill cores.

Figure 2. (Norris et al.) Compilation of oxygen stable isotope ratios for clay-hosted planktonic foraminifera (red symbols), chalk-hosted planktonic foraminifera (blue symbols), and benthic foraminifera (black symbols). The data are compiled from Atlantic and Pacific Ocean sites located between 60°S and 30°N paleolatitude.

Figure 3. (Erba) Mid-Cretaceous integrated stratigraphy, nannofossil evolutionary events and evidence of cooling episodes interrupting the greenhouse conditions. The main igneous events related to the formation of the Ontong Java - Manihiki and Kerguelen LIPs closely correlate with OAEs, isotopic excursions and biotic changes. Timescale: Gradstein et al. (1995). Planktonic foraminiferal zones: Premoli Silva et al. (1999). Nannofossil zones and events: Bralower et al. (1997), Walsworth-Bell & Erba (in prep.), Erba (1986, 1992, unpublished). Oxygen and carbon isotopic curves: Menegatti et al. (1998), Weissert et al. (1998), Jenkyns et al. (1994), Herrle (2002), Wilson & Norris (2001). Igneous events: Larson & Erba (1999), Duncan (2002).

Figure 4. (Leckie et al.**)** Summary of the major geochemical, tectonic, sea level, and plankton evolutionary events associated with the mid-Cretaceous Oceanic Anoxic Events. Note the concentration of evolutionary turnover events (speciation plus extinction) with the OAEs. Also note that OAE1a, 1b, and 2 are temporally associated with increased submarine volcanic activity as indicated by the lower $^{87}Sr/^{86}Sr$ ratios (Bralower et al., 1997), and all three are linked to increased burial of marine organic matter (e.g., Arthur et al., 1987; Erbacher et al., 1996; Larson and Erba, 1999). Leckie et al. hypothesize that submarine volcanism and hydrothermal activity at the spreading centers helped to fuel the elevated levels of marine productivity during the OAEs

by way of iron fertilization of the water column. In addition to submarine volcanism, the strontium isotope record is also influenced by continental weathering and runoff (e.g., Jones and Jenkyns, 2001), and the rise in $^{87}Sr/^{86}Sr$ ratios during the Albian may in large measure record increased weathering rates with rising sea level and global warming, despite the faster spreading rates that sustained high global sea level through much of the Late Cretaceous. The high productivity associated with OAE1d may have been facilitated by an ocean already preconditioned by dissolved iron (from Leckie et al., 2002).

Figure 5. (Holbourn and Kuhnt) Benthic foraminiferal biofacies data for Cretaceous OAE 1a-1d, 2 and 3 do not support a simple model of mass extinctions caused by global anoxia, followed by prolific radiations during the recovery period at the end of OAEs. An alternative model of accelerated faunal turnover within reduced or isolated populations during and following periods of anoxia is proposed. This new model implies that the extent, depth and intensity of oxygen minima within ocean basins varied considerably with time during OAEs. In the case of OAE2, the most significant faunal turnover was in deep sea assemblages, whereas faunal turnovers in shelf and bathyal assemblages mainly reflect sea level change and taphonomic bias.

Figure 6. (Erbacher and Herrle) Temperature indices showing that OAE1b falls into an extremely warm and humid phase of an eccentricity cycle. Climate change forced by precession (monsoon-driven fertility change) and obliquity (temperature change) are also present in the sequence (Herrle et al., 2003a; 2003b).

Figure 7. (Huber et al.) Paleotemperature estimates based on $\delta^{18}O$ analyses of planktic and benthic foraminifer species from the subtropical North Atlantic (Blake Plateau ODP Sites 1049 and1050) and sub-Antarctic DSDP Site 511 and ODP Site 690 (modified after Huber et al., 1995, 2002). Temperatures are estimated using the Erez and Luz (1983) paleotemperature equation and assuming that the isotopic composition of Cretaceous seawater was $-1.0‰_{SMOW}$. Planktonic data are adjusted using the Zachos et al. (1994) correction for paleolatitude. Note that the coolest deepwater temperatures in the Blake Plateau record occurred during the late Albian and early and late Maastrichtian. Brief benthic cooling events are shown at ~100 and 95.5 Ma, but correlative cooling is not observed in the planktonic record from Blake Plateau or in benthic and planktonic

records from southern high latitudes. Higher resolution records and more accurate correlation of the across these "cooling events" to test whether they can be identified globally.

Figure 8. (Jarvis et al.) Sea level change versus carbon isotope stratigraphy. The carbon isotope curve is a five-point moving average of data from the Trunch borehole, eastern England (data from Jenkyns et al., 1994). The $\delta^{13}C$ curve (thick grey line) is plotted against the time scale of Gradstein et al. (1995), calibrated using the base Campanian (83.5 Ma) and base Maastrichtian (71.3 Ma) and assuming a constant sedimentation rate at Trunch. Isotope events are indicated by colored bands. The relative positions of the NW European macrofossil and Tethyan planktonic foraminifer biostratigraphies are based on a carbon isotope correlation with El Kef, Tunisia (Jarvis et al., 2002). The transgressive and regressive events (green and red polygonal boxes, respectively) recognized in Germany (Niebuhr, 1995; Niebuhr et al., 2000) are shown for comparison. Peaks and troughs on the regional sea level curves have been placed relative to the appropriate biostratigraphy. The 'eustatic' curve (Haq et al., 1987) has been re-calibrated by placing the base of TST3.4 at the bottom of the Santonian - Campanian Boundary Event, the base of TST4.1 at the base of the mid-Campanian Event, and the base of TST4.4 at the top of the Upper Campanian Event, and scaling the remainder of the curve accordingly. HST = high-stand systems tract; LST = low-stand systems tract; TST = transgressive systems tract.

Figure 9. (Hancock) Comparison of radiometrically interpolated and biostratigraphically correlated versions of the Haq et al. (1987) sea level curve with the Hancock (1990) sea level curves for northwest Europe the Campanian-Maastrichtian. Differences in the timing of the transgressive peaks and regressive troughs is caused by differences in the biozonal schemes, stage boundary definitions, and time scales that are used for each curve.

Figure 10. (Larson et al.) Timing comparison of the mid-Cretaceous igneous events proposed as causes for the two most prominent geological responses. Ontong Java and Manihiki Plateau formation proposed as cause for OAE 1a (Selli Event) and Caribbean Plateau formation proposed as cause for OAE 2 (Bonarelli Event).

Figure 11. (Duncan) Cartoon depicting a hydrothermal event plume produced by eruption of large volume (~1000 km^3) lava flow during construction of an ocean plateau. High concentrations of certain metals (relative to trace concentrations in sea water) are carried to the ocean surface in the thermally buoyant plume. Many of these metals are normally bio-limiting, so their sudden availability could spur brief periods of high productivity. The metals are removed from the surface at differing rates and fractionated (near field and far field patterns), but ultimately transported to the sea floor on particles.

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