Sea−level and climate fluctuations at the Cenomanian−Turonian Boundary of the Anglo−Paris Basin (Eastbourne) and European Tethyan margin (Cassis and Vergons, southeastern France)

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The Cenomanian−Turonian oceanic anoxic event is associated worlwide with a major marine transgression, coeval deposition of organic rich sediments, and major positive $\delta^{13}C$ excursion. Here we show preliminary results of sea level and climate fluctuations based on sections from the Anglo−Paris Basin (Gun Garden, Eastbourne) and European Tethyan margin (Cassis and Vergons, France), which are characterized by different paleogeographic regimes.

The Eastbourne section, exposed along the seashore cliffs between Beachy Head and Eastbourne, Sussex, England, is about 13m thick, and spans the Cenomanian−Turonian (CT) boundary. It is one of the more expanded C−T transitions in England with a significantly higher sedimentation rate than the condensed sections from the Dover−Folkstone region. A sea−level change marks the base of the section with an abrupt change from the Grey Chalk to the Plenus Marl. This sharp, erosive and burrowed lithological contact is interpreted as a significant sequence boundary. The lower member of the Plenus Marls, including the one meter thick interbedded grey chalk, is considered as a lowstand deposits (SMW). The base of the upper member of the Plenus Marls is interpreted as a transgressive surface. Upsection, sedimentation becomes more calcareous and corresponds to a major rapid transgression. This interval corresponds to a transgressive system track, due to the presence of several calcarenitic layers with discrete harground surfaces and abundant Inoceramus prisms deposited by current winowing that indicate a period of starvation in the basin during the rising sea−level. The total organic content is very low, ranging from 0.02 to 0.25% of the sediment. Bulk rock and clay mineralogy indicate that the CT transition was characterized by an overall sea level highstand, interrupted by high frequency and high amplitude sea−level lows under cool−temperate and dry climate conditions. Positive $\delta^{18}O$ values suggest short periods of overall oceanic cooling. These forced regressions may have been triggered by tectonism and/or glacio−eustasy.

The Cassis section is located near the town of Cassis at the l'Anse de l'Arène (France). The 95m thick sequence consists of basinal deposits, characterized by regularly cyclic alternation of pelagic limestone and marls. Similar to the Gun Garden section, the total organic carbon content is low ( excursion observed at Eastbourne have been similarly observed at Cassis. The fauna suggests that the section is both shallow (middle neritic) and boreal. These conditions have favored a different foraminiferal assemblage that indicates a higher oxygen content for the W.archeocretacea Zone that at Eastbourne. At Cassis, sediments were deposited near the upper limit of the oxygen minimum zone.

The Vergons section is located in the eastern part of the Vocontian Basin (France), and is characterized by deeper paleo−environments with ryhthmically alternating marls and marly limestones layers. The top of R.cushmani Zone is marked by an erosive contact that suggests the presence of a significant hiatus. Above this hiatus, the W.archeocretacea Zone is characterized by deposition of the main black shale horizon (BSH) of the Thomel level, which consists of laminated layers enriched in organic matter (1−2%). The decimeter scale laminations of the BSH and the bioturbated organically depleted marls indicate that the oxygen minimum zone periodically reached the basin floor. Rhythmic deposition ends abruptly in the upper part of the laminated layer which is affected by significant slumping.

These sections indicate that paleogeographic features significantly influenced the distribution of organic rich sediments. However, high frequency climatic and sea level flucutations (including glacio−eustatic changes?) may be a promising alternative hypothesis to explain the Cenomanian−Turonian anoxic event.

The Cretaceous Carbon Cycle: Interpreting the Carbon Isotope Record

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Variations in the carbon isotopic compositions of marine carbonate and organic carbon provide a record of changes in the fraction of organic carbon buried through time and may provide clues to changes in rates of weathering, sources of organic carbon, and possibly changes in carbon fluxes from volcanism and gas hydrate decomposition events. Paired carbonate and organic carbon isotope determinations provide a possibility of interpreting not only changes in global carbon cycling, but changes in atmospheric $pCO_2$ as well. Interpretations of these types of data are typically rather qualitative, for example, the common assertion that a positive carbon isotope excursion indicates an increase in the rate of burial of organic carbon.

A quantitative approach to carbon cycle modeling provides some surprising insights, some of them counterintuitive. For this purpose, I employ a simple model of the global carbon cycle which is subjected to a number of different perturbations on scales and magnitudes appropriate to the Cretaceous. In addition to standard considerations of carbon mass and isotopic fluxes to the ocean−atmosphere system from weathering and volcanism and fluxes of organic carbon and carbonate−carbon to sediments, the model incorporates sensitivity of the photosynthetic carbon isotope effect to changes in $pCO_2$ . The inclusion of this parameter leads to unexpected carbon isotope responses to forcing that causes increased rates of organic carbon burial. I will compare the model simulated carbon isotopic responses for several experiments to paired carbonate− and organic−carbon records to illustrate how these records might be interpreted in light of the model response. In particular, I will focus on characteristics of the Aptian OAE 1a event and demonstrate the diffences in system response to various volcanic forcing scenarios as opposed to that produced by a large release of methane from gas hydrates. The results of carbon cycle modeling suggest that gas hydrate release cannot be the primary cause of the OAE and carbon isotope variations, whereas a "superplume" event appears to best produce the responses seen in the sedimentary and geochemical record. Carbon cycle modeling suggests that the Cenomanian−Turonian (OAE 2) event is not clearly related to either increased volcanic carbon dioxide degassing or to methane clathrate release.

Twenty Years of Cretaceous Climate Modeling

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The first General Circulation Model simulations of Cretaceous climates were published exactly twenty years ago. By modern standards, the models were primitive. These early experiments were based on a 60 to 90 day simulation with fixed insolation (January or July), with an energy balance ocean lacking any heat capacity (so called "swamp" ocean that providing a source of moisture and enabled evaporative cooling and albedo to be included in the surface temperature equation), and a terrestrial albedo to account for surface vegetation. Our focus was on the extent to which continental geometries would alter the structure of the circulation, whether sea level had a direct impact on atmospheric warmth, and whether these changes would allow simulation of a reduced equator−to−pole temperature gradient. The progress of the last two decades is noteworthy. Paleoclimate modeling has followed closely in the footsteps of climate modeling in general with improvements in radiative transfer calculations, the addition of a mixed layer ocean and the seasonal cycle, the addition of fully resolved ocean models, and the inclusion of vegetation as an interactive component of the climate system. Our ability to collect and interpret the wealth of geochemical, physical and biologic information about the Cretaceous has also expanded considerably. It is clearly the marriage of models with Cretaceous observations that has yielded remarkable advances in our understanding. We are much closer to recognizing that "the Cretaceous" includes a remarkable diversity of climates. We have made substantial progress in attempting to "predict" climate parameters that can be closely tied to proxy information. In the near future, we can expect to see such things as biomes, isotopic composition, and ocean biogeochemical cycles as standard elements of paleoclimate modeling. To a considerable degree, we now recognize what types of observations really challenge the models and visa versa. The marriage of models and data has focused our attention on tropical sea surface temperatures and the nature of high latitude continental interiors. We are approaching a whole new set of problems as we begin to explore the significance of the coupled system response, including such remarkable avenues as the role of run−off in governing the deep circulation. Yet, explaining (and simulating) the nature of Cretaceous warmth and the nature of poleward heat transport during times of polar warmth have remained intriguing problems. Without a doubt, the Cretaceous is an example of how a single forcing factor is inadequate to describe the climate change recorded in Earth history, and is an example of how the coupled system must play a key role in climate change.

Cyclic fluctuations in the composition of organic matter of OAE3 black shales (ODP Site 959, off Ivory Coast/Ghana)

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The importance of Cretaceous oceanic anoxic events as key mechanism for the development of large organic carbon sinks and its relationship to rapid climate changes is widely acknowledged. Our study focuses on organic and inorganic geochemical analysis of sediments accumulated during the final, Coniacian−Santonian OAE3, in the Ivory Coast basin at ODP Site 959 (off Ivory Coast/Ghana). The composition of organic matter throughout the sedimentary record at Site 959, timing of changes in its composition, and the identification of global or regional controls on the sedimentation are of special interest.

Two opposing depositional modes are supported by our data: a black shale mode with TOC content up to 16%, and a background mode with TOC concentrations of about 3%. Maceral analysis reveals an overall dominance of marine amorphous organic matter (AOM). Apart from AOM, particulate marine organic matter dominates in black shale samples resulting in oil−prone kerogen Type I. The temporal occurrence of Isorenieratane derivates, biomarkers indicative for photic zone anoxia, evidence extreme depositional conditions off Equatorial West−Africa. In contrast, sediments deposited during the background mode mainly consist of kerogen Type II/III organic matter with considerable contribution from terrigenous sources.

To identify global and/or local controls on the sedimentation at Site 959, analyses of d18O and d13C isotopes are shown and compared to carbon− and oxygen−isotope stratigraphies from England and Italy, as reported from the literature.

Paradox of the Late Turonian Record at DSDP Site 511 (60°S paleolatitude)

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Within data supporting warm mid−Cretaceous climates, paleotemperature estimates from the late Turonian at DSDP Site 511 (Falkland Plateau) stand out as problematic. Huber et al. (1995) reported planktonic foraminiferal $\delta^{18}O$ values as light as −4.39 per mil (PDB). Assuming a range of reasonable local water $\delta^{18}O$ estimates (−1.2 to −1.75 per mil SMOW), the data reported by Huber et al. indicate upper ocean waters as warm as 28−30°C at ~60°S paleolatitude in the Late Turonian. In the modern ocean, such temperatures are typical of the western Pacific tropical warm pool. In the geologic record, such temperatures are currently unsupported by other data from equivalent latitudes in either hemisphere for any time period.

We have obtained a detailed record of planktonic and benthic isotope values across the negative $\delta^{18}O$ shift reported by Huber et al. (1995). The planktonic foraminiferal and calcareous nannofossil assemblages include cosmopolitan species that are associated with normal, open marine depositional settings. The foraminifera exhibit excellent preservation. Shells are translucent and chambers are hollow. Surface ornamentation is preserved. No overgrowths or infilling material is present. Primary wall microstructure is preserved, with distinct shell layering and wall pores clearly visible. A Late Turonian age is assigned to these samples based on co−occurrence of the calcareous nannofossil *Kamptnerius magnificum* and the planktonic foraminifera *Marginotruncana marginata* (=*Globotruncana bulloides* of Huber, 1995) and *Praeglobotruncana stephani*. Strontium ratios indicate that the 511 event may be age equivalent with very depleted planktonic forams from tropical Atlantic Site 144 (5°N paleolatitude; Wilson et al., 2002).

The new isotope data are consistent with those published earlier. There is an abrupt change in planktonic $\delta^{18}O$ at 412.18 mbsf where planktonic oxygen values decrease by ~2 per mil. *M. marginata* yielded the lightest $\delta^{18}O$ measurement (−4.66 per mil PDB). Benthic values show little change through the study interval, which makes it appear that the event is one of surface "freshening." Reasonable mixing ratio calculations show that, assuming no change in freshwater $\delta^{18}O$, the local freshwater component would have had to increase from 5% before the event to 27% during. In that case, a salinity decrease of ~7 psu would be expected. However, foram and nannofossil assemblage changes indicate, if anything, a change to more normal marine conditions within the depleted $\delta^{18}O$ interval.

A decrease in freshwater $\delta^{18}O$ also does not appear to be a plausible mechanism: it would entail at least a 40 per mil decrease, to values like that of modern central Antarctic snowfall. In fact, if some warming accompanied the Site 511 event (a change supported by foram and nannofossil assemblage changes), the high latitude precipitation would have become *less* depleted, as indicated by climate models that include water isotope tracers. The comparison of ocean circulation model results and bottom water temperatures inferred from benthic $\delta^{18}O$ indicates that the 511 event is unlikely to have resulted from a surface water temperature increase to 32°C (estimate based on *M. marginata* $\delta^{18}O$). The lack of evidence of a salinity decrease, detrital influx or benthic change argue against this being a glacial meltwater record.

We are currently unable to explain how surface waters over Falkland Plateau became highly 18O−depleted. The paradoxes presented by the Site 511 data require that this interval be sampled at other locations outside the high latitude South Atlantic basin and that multiple−proxy techniques be applied to these new Late Turonian sections when they are found.

Possible Atmospheric $CO_2$ Extremes of the Mid−Cretaceous

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Mid−Cretaceous $CO_2$ estimates from proxy records and numerical carbon cycle models have a range of more than 4000 ppmv, which presents considerable uncertainty in understanding the possible causes of warmth for this interval. We examine the question of late Albian through Turonian radiative forcing from an inverse perspective: If general circulation models (GCMs) can be used to accurately predict surface temperatures and mid−Cretaceous surface and ocean temperatures can be reasonably estimated from proxy data, then GCMs that reproduce mid−Cretaceous temperature estimates can be used to define plausible greenhouse gas concentrations for the mid−Cretaceous. Upper ocean water temperatures are estimated from planktonic $\delta^{18}O$ data and compared against temperatures predicted by mid−Cretaceous atmospheric model experiments in which $CO_2$ is varied from 500 to 7500 ppmv. In the GCM, reduced solar luminosity and possible increased $CH_4$ are also taken into consideration. The results indicate that 4500−5000 ppmv $CO_2$ is required to match the warmest upper ocean temperatures inferred from $\delta^{18}O$ of well−preserved planktonic foraminifera, excluding late Turonian data from ODP Site 511. Approximately 900 ppmv $CO_2$ produces a good match between the model and minimum tropical temperatures estimates for the mid−Cretaceous. An ocean model forced by these two extremes in surface conditions brackets nearly all available bottom water temperature estimates for this interval.

When very depleted (as light as −4.6 per mil PDB) late Turonian planktonic $\delta^{18}O$ values from Site 511 (*Huber et al.*, 1995; *Bice et al.*, in prep.) are included in the model−data comparison, then 6500−7500 ppmv $CO_2$ is required to produce a match to upper ocean temperatures. In the ocean model, this surface forcing produces warmer bottom water temperatures than are indicated by any existing mid−Cretaceous benthic $\delta^{18}O$ data. The meaning of the Site 511 late Turonian data is currently unresolved.

Our results indicate that the models support nearly the entire range of mid−Cretaceous $CO_2$ proxy reconstructions. This suggests that, rather than contradicting one another, proxy $CO_2$ techniques with high temporal resolution may capture true variability in $CO_2$ concentrations and that mid−Cretaceous atmospheric $CO_2$ varied by several thousand ppmv on timescales of 2 million years or less. The ocean model suggests plausible buoyancy forcing conditions responsible for changes in the sites of deep water formation in the mid−Cretaceous. The dominant change is from deep water formation in the high latitude region of one hemisphere to the other hemisphere in response to warmer/cooler surface temperatures and an increased/decreased hydrologic cycle.

Huber, B. T., D. A. Hodell and C. P. Hamilton, Middle−Late Cretaceous climate of the southern high latitudes: Stable isotopic evidence for minimal equator−to−pole thermal gradients, GSA Bull., 107, 1164−1191, 1995.

What would a Cretaceous glaciation look like?

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The Cretaceous has traditionally been thought of as an interval during which no continental polar ice−sheets existed, based on quantitative and semi−quantitative evidence for surface ocean and coastal continental temperatures much warmer than the modern in polar regions, as well as a lack of obvious ice−rafted sediments. Although the reconstruction of Cretaceous global sea level change is imperfect and debate over any one feature is common, rapid global sea level changes on the order of 10 to 70 meters are typical of Cretaceous reconstructions. Yet, true eustatic sea level change of 10−70 m on the time scale of tens to hundreds of thousands of years is difficult to explain in the absence of ice volume changes as a mechanism. Now, a growing body of literature exists that suggests that the assumption of a Cretaceous "greenhouse" earth free of continental ice should be re−examined. What is the likely isotopic composition of an ice−sheet formed during intervals of Cretaceous climate conditions and at what size is such an ice−sheet likely to produce a significant shift in seawater isotopic composition?

Using a version of the GENESIS atmospheric general circulation model (GCM) modified to include water isotopes ($\delta^{18}O$ and D/H), we have performed two preliminary experiments with mid−Cretaceous boundary conditions. A run with 900 ppm $CO_2$ produces SSTs consistent with the coolest upper ocean temperatures inferred from late Albian−Turonian planktonic oxygen isotope ratios. The GCM run with 4500 ppm $CO_2$ matches maximum inferred upper ocean temperatures. Increasing atmospheric $CO_2$ and decreasing the equator−to−pole surface temperature gradient reduces the gradient in precipitation $\delta^{18}O$ substantially compared to the modern. Tropical freshwater $\delta^{18}O$ is 2−3 ‰ (SMOW) more depleted than the modern and high latitude winter precipitation is 6 ‰ (at 60° lat.) to 24 ‰ (at 90° lat.) heavier than modern. Winter precipitation falling over Antarctica has a mean composition of ~ −14 to −20 ‰ SMOW (compare to the modern ~ −50).

These preliminary results have at least two important ramifications for interpreting warm Cretaceous climate records:

1) If the mean isotopic composition of ice that formed at high latitudes was no less than −20 ‰, then an ice volume equivalent to 60% of the modern Antarctic ice−sheet would produce only a 0.2 ‰ shift in the mean ocean $d_w$ value. This means that a substantial volume of ice could form/decay without being detectable in benthic $\delta^{18}O$ records. In the sequence of events reflected in the record during ice growth, eustatic sea level fall may therefore be the only "given" and is, indeed, generally accepted as having occurred through the Cretaceous.

2) A lower latitudinal gradient in freshwater $\delta^{18}O$ would result in a lower gradient in upper ocean $d_w$, relative to the modern. Use of the latitudinal correction for $d_w$ based on modern GEOSECS data (Zachos et al., 1994) has therefore consistently *over*estimated (by a few degrees) tropical upper ocean temperatures and dramatically *under*estimated high latitude temperatures. This seems to exacerbate the problem of Cretaceous polar ice growth.

Cretaceous nannoplankton evolution and diversity

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Cretaceous coccolithophores (and associated calcareous nannofossils) reached levels of evolutionary diversity and, arguably, carbonate production that had not been achieved before and have not been seen since, yet the period was characterised by relatively stable evolutionary trends (dominantly diversity increase) and was bracketed by far more dramatic events − catastrophic extinctions at the Cretaceous/Tertiary boundary and considerable taxonomic turnover across the Jurassic/Cretaceous boundary. Having said this, many authors have alluded to possible relationships between nannofossil evolution and major Cretaceous global environmental change and, specifically, the oceanic anoxic events of the mid−Cretaceous.

New nannoplankton diversity data reveal that the Cretaceous saw relatively rapid and continuous diversity increase to an "all−time" maximum in the late Campanian. Three main intervals of increase − the Berriasian−Hauterivian, Aptian−Albian and Turonian−Campanian − were interrupted by diversity minima in the Barremian and Cenomanian. The data reveal no clear relationship between long−term diversity trends and currently−recognised major global environmental change events in the Cretaceous. Oceanic Anoxic Events 1 (early Aptian) and 2 (late Cenomanian) occurred well within nannoplankton diversity minima and were followed in both cases by periods of protracted diversity increase. However, the most rapid evolutionary increases broadly correlate with cooler climate intervals, and enhanced species diversity in the Campanian was arguably related to the onset of late Mesozoic climatic cooling with much of the diversification the result of greater palaeobiogeographic differentiation, and in particular the evolution of high−latitude−restricted floras. The Berriasian to Hauterivian increases were also accompanied by increased endemism, but included a greater number of low−latitude restricted groups, including the enigmatic nannoconids.

In contrast, Cenozoic nannoplankton diversity patterns are markedly more variable than those of the Cretaceous, and there is good correlation between diversity and climate trends. Notably, diversity maxima are associated with warm intervals and minima correlated with cooler intervals. This suggests that climate−driven changes in ocean productivity and gyre habitat−space may have exerted an important control over the global diversity of the group in the Cenozoic, an explantion that is currently difficult to apply to their Cretaceous counterparts.

Detailed C−isotope analysis of the Cenomanian−Turonian Boundary Oceanic Anoxic Event and the potential link to methane hydrate dissociation

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The Cenomanian−Turonian Boundary Oceanic Anoxic Event (OAE2) led to deposition of organic−rich sediments on a global scale. However, the origin of this event is still unclear. Recently, the OAE has been linked to methane hydrate dissociation based on large and abrupt negative carbon isotope excursions (−5 to −8 per mil) in the $\delta^{13}C$ record of calcium carbonate from the Bass River borehole in the New Jersey coastal plain (ODP 174AX). The dissociation of large volumes of methane hydrate in continental margin sediments could have depleted oxygen in the deep ocean and caused the OAE.

Three sections were sampled at high resolution (1−3 cm) to test the methane hydrate dissociation hypothesis. Two localities are in the Western Interior Basin (Cuba, Kansas and Pueblo, Colorado) and the other locality is the Bass River borehole. Carbon isotopes were analyzed on the organic carbon and carbonate fractions of sediments. Methane hydrate dissociation should result in an abrupt negative carbon isotope excursion in both the organic carbon and calcium carbonate fractions.

Almost no change in the $\delta^{13}C$ values of the organic fraction coincide with those in carbonate suggesting that methane hydrate dissociation was not responsible for initiating the Cenomanian−Turonian Boundary OAE. Diagenesis is likely responsible for the large and abrupt negative $\delta^{13}C$ excursion observed in calcium carbonate. More specifically, contemporaneous recrystallization of calcium carbonate and oxidation of organic matter appears to have caused the extremely low carbonate carbon isotope values.

Marine Productivity during Oceanic Anoxic Events: A New Outlook

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Transient climate events often lead to profound changes in ocean circulation. This modified circulation has in turn led to increase or decrease in the supply of nutrients to surface waters, both delivered from the continents via runoff and upwelled from the deep ocean. Paleoceanographers have often painted a black and white picture of productivity change during transient climate events. For example, Cretaceous Oceanic Anoxic Events (OAEs) have been thought of as periods of high oceanic productivity as indicated by the abundance of siliceous microfossils in particular black shale horizons and by planktic foraminiferal carbon isotope data. We present nannoplankton assemblage data illustrating that it is impossible to generalize about productivity changes on an ocean−wide basis for transient climate events.

Nannoplankton assemblage data from sections in Kansas in the Western Interior Seaway and the New Jersey coastal plain indicate reduced productivity at the onset of OAE2 at the Cenomanian/Turonian Boundary. A marked decrease in the relative abundance of Biscutum constans, a species that is widely thought to be an indicator of high−fertility environments, is observed at the onset of the event. Conversely, taxa that are interpreted as indicative of oligotrophic environments increase in abundance. In both sections, productivity appears to increase in the later part of the event. Similar trends have been observed by Paul et al. (1999) and Gale et al. (2000) for contemporaneous shelf sections from northwest Europe. Combined with other microfossil assemblage and geochemical data, nannoplankton assemblage data suggest sequestration of nutrients in open ocean environments and starvation of the shelf and epicontinental seaways during OAE2. This is in marked contrast to current hypotheses regarding the origin of anoxia and organic matter accumulation.

In summary, transient climate events should not be thought of us resulting in ocean−wide increases or decreases in productivity. Instead, these events appear to have resulted in profound changes in the distribution of nutrients in the ocean. These changes had significant effects on marine biotas and may be responsible for at least part of the turnover that took place during short−lived climate events such as OAE2.

Molecular markers of plankton preserved in lower Aptian sediments (OAE 1a)

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Series of mid−Cretaceous organic−rich claystones and porcellanites were recovered during ODP Leg 198 on Shatsky Rise in the west−central Pacific. The abundance, nature, and origin of the organic matter in select intervals were examined by shipboard procedures employing elemental analysis, Rock−Eval pyrolysis, and gas chromatography−mass spectrometry (GC−MS). Remarkable amounts of organic carbon (up to 35% Corg) occur within the early Aptian Oceanic Anoxic Event (OAE 1a) at Sites 1207 and 1213, which are among the highest values ever recorded for pelagic Cretaceous sequences. They attest to the extraordinary nature of the depositional conditions that led to enhanced sequestration of type I kerogen rich in algal and bacterial organic matter. The biomarker composition of the intervals provides clear testimony of the exceptional preservation of organic matter, both in its abundance and unaltered character. The hydrocarbon and ketone biomarkers show stratigraphic consistency in the compositions of compounds attributed to eukaryotes (notably sterenes and sterones), but variability in prokaryotic (especially hopanoid) distributions and abundances. The constituents included unprecedented series of 2−methyl−17β(H),21β(H) hopanes and hopanones diagnostic of cyanobacterial contributions. Alkenones, components only biosynthesized by haptophyte algae, occur in one of the lower Aptian samples, which extends the geological record of the occurrence of these paleotemperature proxies by 15 My. Evidence of contributions from methanogenic bacteria among extractable biomarkers is sparse, in stark contrast to characteristics observed elsewhere in other OAE.

These results provide evidence of the biological origins of the organic matter in selected intervals of the early Aptian and help describe their environment of deposition. They suggest changes in prokaryote populations related to the conditions that led to increased sequestration of organic matter and help describe the phytoplankton communities extant during OAE 1a.

Mid−Cretaceous Deposition and Erosion by Deep−Sea Currents Along the Continental Rise, Deep Eastern Gulf of Mexico

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A prominent mid−Cretaceous sequence boundary (MCSB) divides the rock record in the Gulf of Mexico basin into two major depositional episodes and marks a major turning point in Gulf history. The nature and orgin of this boundary is still controversial. Along the deep eastern Gulf continental rise the MCSB is a prominent unconformity marked by truncation below and onlap above.

The upper part of the Lower Cretaceous section in the deep eastern Gulf is characterized by deep−sea fan systems oriented parallel to the margin. In places lying directly below the the MCSB are large southward−prograding mounds or buildups. Both of these features are interpreted to have been deposited by strong south−flowing contour currents. These currents apparently developed and intensified during the middle Cretaceous as the carbonate margins rimming the basin steepened through time, further restricting the basin. They flowed south along the base of the Lower Cretaceous carbonate margin and then out of the basin through the only deepwater outlet lying between Florida and Yucatan, possibly as part of a larger boundary current system in the Atlantic.

The overlying MCSB is characterized by major truncation of Lower Cretaceous units, probably due to extreme intensification of the currents caused by major mid−Cretaceous drops in sea level. This suggests that the MCSB represents a true erosional sequence boundary and not just regional onlap, a flooding surface or a drowning unconformity as suggested by other authors.

Geochemisty of the oldest Pacific and Atlantic oceanic crusts: tectonic and geodynamic implications

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Complete major and trace element and Sr−Nd−Pb isotopic compositions for samples of the oldest Pacific and Atlantic oceanic crusts collected by Deep−Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP) have recently become available. Data for the Jurassic−Early Cretaceous (170−130 Ma) mid−ocean ridge basalts (MORB) recovered in the central and northwestern Pacific Ocean indicate that these basalts were generated by degrees and pressures of melting identical to those of modern Pacific mid−ocean ridges, and are geochemically identical to Pacific normal−MORB. In general, these Mesozoic Pacific MORB are depleted in highly incompatible elements and display a wide range in Nd and Pb isotopic ratios (eNd(T) = 8.4−11.6; 206Pb/204Pbi = 17.9−18.6) but have a low and uniform Sr isotopic composition (87Sr/86Sri = 0.7023−0.7026). Compared to the older and modern Pacific MORB, mid−Cretaceous Pacific MORB (=115−100 Ma) are moderately to strongly enriched in highly incompatible elements with an "enriched mantle" isotopic affinity. The shift in MORB composition coincides with the onset of effusive mid−Cretaceous intraplate volcanism in the Pacific and reflects widespread contamination of the Pacific upper mantle with materials derived from the plumes or plume heads responsible for mid−Cretaceous oceanic plateaus and seamount chains. Data for the oldest central Atlantic oceanic crust, on the other hand, show that MORB generated from about 160 to 120 Ma are the ones that display clear isotopic and chemical signals of plume contamination (e.g., 87Sr/86Sri = 0.7032 to 0.7036, eNd(T) = +6.2 to +8.2, incompatible element patterns with positive Nb anomalies). Plume contamination signals are muted or absent in crust generated between 120 and 80 Ma, which resembles modern Atlantic normal−MORB. The plume−affected pre−120 Ma Atlantic MORB are isotopically similar to lavas from the Ontong Java Plateau and mid−Cretaceous Pacific MORB. The strongest plume signature is displayed near the center of the Central Atlantic Magmatic Province (CAMP), a region covered by a brief, but massive flood volcanism at ~200 Ma (near the Triassic−Jurassic boundary) on what are now the continental margins of eastern North America, southwestern Europe, West Africa, and northeastern South America. However, the hotspots presently located nearest this location in the mantle reference frame do not appear to be older than the Late Cretaceous and are isotopically distinct from the oldest Atlantic MORB. The widespread plume contamination of the nascent Atlantic upper mantle, but with a lack of evidence for a long−lived volcanic chain and/or oceanic plateau associated with this plume, indicates an origin different from that of the Pacific upper mantle that produced mid−Cretaceous MORB. The enriched signature of the early Atlantic crust, and possibly the eruption of the CAMP, were caused by a relatively short−lived, but large volume plume feature that was not rooted at a mantle boundary layer.

Globally synchronous long−term climate changes during the mid− to Late Cretaceous?

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New and previously published oxygen−isotope data, derived from calcareous deep−sea sedimentary components recovered by the Deep Sea Drilling Project (DSDP) and Ocean Drilling Program (ODP), are presented in the context of long−term mid− to Late Cretaceous (Aptian to Maastrichtian) temperature change. Oxygen−isotope records include data from the Southern Hemisphere (ODP Holes 762C, 763B and 766A cored on Exmouth Plateau, off western Australia), equatorial Pacific Ocean (DSDP Site 463, Mid−Pacific Mountains) and Northern Hemisphere (Italian Scaglia and English Chalk outcrop sections). Interpolation of the majority of these isotopic data onto a numerical timescale, using independent magnetostratigraphic and biostratigraphic datums, facilitates direct correlation between different localities. Furthermore, comparison to other palaeoclimate data sets indicates that globally synchronous climate variability occurred on both hemispheres of the Cretaceous globe during Aptian to Maastrichtian time.

A marked decrease in oxygen−isotope ratios occurred across the Aptian−Albian transition, a change that is conventionally interpreted as a marked warming event. However, a preliminary application of Mg/Ca palaeothermometry suggests that the Aptian−Albian oxygen−isotope record could in fact reflect massive input of oxygen−16 into the global oceans, most likely in relation to a deglaciation episode. Intriguingly, this latter interpretation may help to reconcile the glendonite and dropstone evidence for a cool, or possibly even sub−freezing, late Aptian climate with the purported mid−Cretaceous 'greenhouse' world. Subsequent to the Aptian−Albian isotopic transition, steady long−term warming occurred until Albian−Cenomanian boundary time, with cooling post−dating the earliest Cenomanian warm event, and a climate optimum attained sometime during Cenomanian−Turonian boundary time. The most rapid climate change, a marked cooling of climate, occurred between the mid− and late Turonian, and is consistent only broadly with an hypothesis that sedimentary organic−carbon burial during the Cenomanian−Turonian boundary Ocean Anoxic Event sequestered atmospheric carbon dioxide and initiated a reverse greenhouse effect. Subsequently, temperatures increased, or at the very least remained constant, during Coniacian and Santonian time, before continually decreasing through the Campanian and Maastrichtian; the latter long−term deterioration of climate apparently slowed during the middle Campanian.

Initial comparison of oxygen−isotope data to available geological atmospheric carbon−dioxide proxies (sea−floor spreading and oceanic plateaux production rates, strontium isotopes, and continental land area and a sea level curve) indicates an inconsistent relationship between a greenhouse−forcing mechanism and mid− to Late Cretaceous climate evolution. For example, the late Aptian is associated with the highest crustal−production rates, and hence greatest inferred volcanic out−gassing of carbon dioxide, during the mid− to Late Cretaceous, but paradoxically is associated with oxygen−isotope and sedimentological (glendonite and dropstone occurrence) evidence for cool, and possibly even sub−freezing, palaeotemperatures. Consequently, additional research is required in order to understand more fully those climate−forcing mechanisms that resulted in the long−term evolution of climate during the enigmatic mid− to Late Cretaceous geological interval.

An integrated calcareous microfossil biostratigraphic and carbon isotope stratigraphic framework for the La Luna Formation, western Venezuela

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The Cretaceous La Luna Formation is the most important petroleum source rock in Venezuela and possibly the most productive in the world. Despite its significance, the biostratigraphy of the formation is not well known. The age has long been in dispute. Most work has previously been done on isolated sections and has not included all members of the formation. Published data are sparse. We have carried out detailed nannofossil and planktic foraminiferal biostratigraphic studies of a cored borehole and five outcrop sections from the Maracaibo Basin of Western Venezuela. Microfossil biostratigraphy combined with carbon−isotope stratigraphy provides a high−resolution stratigraphic framework.

In general planktic foraminifera have fair to good preservation and nannofossils are poorly preserved. Many of the Cenomanian to Campanian planktic foraminiferal marker species are present, permitting the application of a traditional zonal scheme. An informal nannofossil biostratigraphic zonal scheme based primarily on dissolution resistant species has been developed. Integration of these zonal schemes has enabled the correlation of changes in carbon isotope ratios to global C−isotope stratigraphy. The results have been used to estimate temporal variation in sedimentation rates as well as to reconstruct depositional patterns across the Maracaibo Basin. The framework developed allows a revised understanding of temporal and spatial patterns of organic rich sediments in the La Luna Formation throughout the basin.

Cretaceous Ice Sheets: A Modeling Perspective

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A coupled GCM−dynamical ice sheet model is used to investigate the possibility of significant Antarctic glacial ice during the Cretaceous. The model is used to test the sensitivity of the climate−cryosphere system to changes in paleogeography, atmospheric CO2, orbital configuration, and ocean heat transport. An asynchronous GCM−ice sheet coupling scheme allows for long ($10^6$ year) integrations of ice sheet initiation and subsequent variability though multiple orbital cycles.

Preliminary model results support the existence of isolated ice caps on high plateaus and mountainous regions of the Antarctic continental interior despite the overall warmth and high CO2 of the Cretaceous. The model produces highly dynamic ice caps, growing and shrinking in response to orbital (astronomical) forcing, with the greatest variability in ice volume occurring during periods of high eccentricity. With high eccentricity, south polar latitudes experience exceptionally cool summers (and minimal summer ablation) when obliquity is low and precession places aphelion during austral summer. Warm summers occur when obliquity is high and precession aligns perihelion with austal summer. In GCM−ice sheet simulations of the Paleogene, a specific range of atmospheric CO2 (2x−3x present values) and high eccentricity orbits produce astronomically paced changes in ice volume large enough to account for tens of meters of eustatic sea level change, but without the ice caps reaching the coast. Similar climate−cryosphere behavior is possible during the Cretaceous. These results suggest significant glacial ice was possible during the "greenhouse" climates of the Cretaceous and ice volume response to orbital forcing may have been paced by the 400 kyr eccentricity cycle. While the existence of highly dynamic glacial ice was possible during the overall warmth and elevated CO2 of the Cretaceous and Eocene, simulations of earliest Oligocene glacial inception suggest CO2 values would have had to drop below 3x CO2 for the continental−scale glaciation of Antarctica. During the Cretaceous, the proximity of Australia and India to Antarctic increased southern hemisphere continentality. Thus, the CO2 threshold value for glacial inception was likely different for the Cretaceous than the earliest Oligocene. Additional GCM−ice sheet simulations are underway to better constrain the "greenhouse" glacial history of the Cretaceous and to explore ice sheet behavior under different values of CO2.

Thermal and Compositional Effects of Ocean Plateau Formation: Consequences for Cretaceous Ocean Anoxic Events

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A current popular model for the sporadic occurrence of ocean 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. This proposed connection is far from accepted, and important unresolved aspects include the timing of events and yet−to−be−proved synchroneity of volcanism and OAEs, the sensitivity of phytoplankton to bio−limiting (and toxic) trace metals, the difference in biotic responses at various OAEs, and the source of the hydrothermal inputs (sea floor spreading centers or ocean plateaus?).

Important factors that could help distinguish ocean plateau (surfacing mantle plume) from sea floor spreading (new centers or increased rates) hydrothermal inputs to the oceans are: (1) the timing and duration of volcanic activity, (2) trace metal patterns created by degassing vs water−rock hydrothermal exchange, (3) depth of eruptions and thermal buoyancy of warm water plumes, and (4) scale of heating of deep ocean water. The abrupt nature of changes in redox conditions and sediment composition at OAEs is hard to reconcile with more gradual changes in sea floor spreading conditions. Trace metals enter a magmatic gas phase (governed by volatility) in different proportions to their partitioning in low temperature water−rock reactions. The construction of ocean plateaus to shallow water depths and the large volume of single eruptions favor warm water plumes that rise to the ocean surface; hydrothermal plumes from spreading centers do not rise above ~1km above the sea floor in today's ocean. The sensible heat and latent heat released by single large (~1000km3) lava flows could raise the temperature of a significant volume of the deep ocean, with possible effects being de−stabilization of gas hydrates and breakdown of water column density stratification.

Ocean drilling can make a major contribution to investigating the first two of these subjects. High resolution studies have and will 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.

Cycle stratigraphy and chemostratigraphy of Cenomanian−Turonian (Late Cretaceous) shallow−through deep−marine carbonates and siliciclastics, southern Mexico

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Albian through Turonian marine deposits are well exposed along a westward−dipping carbonate platform in southern Mexico (Guerrero state). The Albian through early Turonian Morelos Formation (800 m) is composed of weakly cyclic subtidal through intertidal carbonates (peloidal wackstones to skeletal grainstones) and is abruptly overlain by the Turonian Mexcala Formation ($2000^+$ m) which is composed of pelagic limestone−marl rhythmites and/or terrigenous turbiditic mudstones and sandstones. Stratigraphic and geochemical studies of these shallow− to deep−water deposits at four locations across the platform−to−basin transition provide an opportunity to evaluate the relationships between changes in sea−level, stable isotopes, siliciclastic input, total organic carbon (TOC), and changes in marine biota.

The upper few 10's of meters of the shallow subtidal Morelos carbonate platform deposits show evidence of gradual deepening and an associated increase in fine siliciclastic input. The ensuing maximum flooding zone (MFZ) is recorded by the abrupt transition from benthic fossil−rich carbonates to thin−bedded pelagic limestone−marl rhythmites and/or thin−bedded terrigenous turbidites (Morelos−Mexcala contact).

Preliminary C−isotope analysis records a positive shift in $\delta^{13}C_{carb}$ of 3.5−4.0 ‰ which begins within the upper 50 meters of the Morelos subtidal limestones (or >50 meters below the MFZ). Uniform elevated C−isotope values continue for 10−15 meters of section and are followed by a gradual negative shift of 3.5−4.0 ‰; the negative shift ends approximately 5−10 meters below the MFZ. $\delta^{13}C_{org}$ trends are variable through this same stratigraphic interval, but generally record a similar magnitude of C−isotopic shift. No obvious trends in TOC values are observed as of yet. Previous foraminiferal biostratigraphy of these deposits suggests that the Cenomanian−Turonian boundary lies at the MFZ (Morelos−Mexcala contact); however, given the observed C−isotope trends, the C−T boundary lies well below the Morelos−Mexcala contact (MFZ) and occurs within shallow subtidal carbonates.

Cretaceous climate changes: a paleobiological perspective.

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The Cretaceous was a period of extreme climatic conditions accompanied by major perturbations in biogeochemical cycling, preserved in the geological record as long− and short− term, abrupt and transitional changes. High−resolution integrated stratigraphy has demonstrated that during the Cretaceous a complex series of events affected the ocean−atmosphere system. While we are still taking a census of such events, it has become more and more evident that exogenic and endogenic processes affected and, at least partially, resulted from the evolution of marine and terrestrial biota. Rates of biomineralization played a key−role in the evolution of the oceans, by affecting their chemico−physical−biological conditions as well as the gas exchange between surface seawater and the atmosphere. Organic carbon−rich sediments can be viewed as end−member lithotypes formed under peculiar paleoceanographic conditions hampering biocalcification in both pelagic and neritic environments. The Cretaceous offers a unique opportunity to explore causes and effects of climate changes and their relationship with skeletal mineralogy and biodiversity. Evolutionary rates in both pelagic and neritic environments correlates with carbon and strontium isotope excursions, Oceanic Anoxic Events (OAEs) and climate changes closely coincident with major volcanic−tectonic events.

A first episode of greenhouse climate occurred in the late Valanginian as testified by a globally recorded C−isotope positive excursion, associated with a crisis of pelagic and neritic carbonates and increased evolutionary rates that are interpreted as a nutrification event, perhaps linked to the Paranà volcanism. The late Valanginian warm and humid climate was followed by a cooler Hauterivian−Barremian interval, then replaced by the mid−Cretaceous greenhouse climate representing the most extreme warmth of the past 150 my. OAE1a and OAE2 correlates with the onset and end of such greenhouse conditions, interrupted by some brief cooling events in the Aptian to Cenomanian interval alternating with extremely warm conditions leading to black shale deposition during OAsubEs. In the Late Cretaceous, climate gradually returned to cooler conditions, although the entire water column was much warmer than today. The Turonian−Maastrichtian interval is characterized by an overall cooling trend interrupted by short periods of warming and cooling as documented by changes in biodiversity of planktonic and benthic communities.

The Cretaceous biosphere was severely affected by the peculiar paleoclimatic and paleoceanographic conditions. Biological processes such as photosynthesis and biomineralization affected the organic and inorganic C−cycle as well as adsorption of atmospheric $CO_2$ in the oceans. These biotic sinks for $CO_2$ imply nutrification events and interactions of the C−cycle with other biogeochemical cycles. Large volcanic−tectonic events and greenhouse conditions must have altered the content and distribution of nutrients in the oceans. Hydrothermal megaplumes related to formation of oceanic plateaus and crust probably introduced high concentrations of dissolved and particulate biolimiting metals into the oceans and $CO_2$ in the atmosphere. Under greenhouse conditions, the hydrological cycle and weathering were altered, perhaps accelerating the introduction of nutrients, iron and other biolimiting elements via run−off and eolian fluxes. Subaerial eruptions must have increased the release of volatiles such as $CO_2$ and S and particulate material in the atmosphere and stratosphere, inducing global climatic effects and perhaps diminishing light intensity available for photosynthesis (volcanic winter).

Oceanic Anoxic Event 1b: 45 kyr of orbitally controlled, Tethys−wide anoxia

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For a long time the early Albian OAE 1b was among those Oceanic Anoxic Events we had comparably little knowledge of. Recent high resolution studies of multiple proxies from sections in France and DSDP/ODP sites from the Atlantic resulted in a new and comprehensive picture of this interval. OAE 1b was described from various Tethyan sections including well−known regional marker beds in the Vocontian Basin (Niveau Paquier) and the Umbria−Marche Basin (Livello Urbino). So far, no well−dated occurrences of OAE 1b are known from successions outside the Tethyan realm.

Based on various studies from the Vocontian Basin, the Blake Nose and Mazagan Plateau, we will present a review of these multiple proxy investigations which included planktic and benthic foraminifera, calcareous nannoplankton, palynology, and stable carbon and oxygen isotopes.

Time series analyses from the Vocontian Basin and the Blake Nose Plateau demonstrate that orbital forcing mechanisms probably controlled anoxia and suggest a ~45 kyr duration for OAE 1b. Moreover, they indicate orbital forcing of palaeoproductivity and −temperature, with a dominant precessional signal for surface−water productivity and a dominance of the eccentricity signal for changes in surface−water temperature.

Stable oxygen isotope gradients between benthic and planktic foraminifera, calcareous nannoplankton and palynology suggest a temperature increase at the base of OAE 1b, followed by an increased continental runoff and an pronounced thermohaline stratification during the anoxic interval. Such a scenario implies warm and humid climates prevailing during the OAE 1b.

Whether or not our observations support the Quaternary sapropel model suggested by Erbacher et al. (2001) or a model that favorites monsoonal activity and eccentricity−driven temperature changes as the driving mechanisms for OAE 1b (Herrle et al., in press) remains to be discussed. However, our results clearly demonstrate the great variability of causes for Cretaceous Oceanic Anoxic Events and the need for more, globally distributed high resolution multiple proxy studies of hopefully diagenetically uncompromised sections.

Erbacher, J., Huber, B.T., Norris, R., Markey, M. (2001): Intensified thermohaline stratification − a possible cause for Cretaceous oceanic anoxic events. Nature, 409, 325−327.

Herrle, J.O, Pross, J., Friedrich, O., Hemleben, Ch. (in press): Short−term environmental changes in the Cretaceous Tethyan Ocean: Micropalaeontological evidence from the Early Albian Oceanic Anoxic Event 1b. Terra Nova.

Landscape denudation as a link between wildfires and bacterially dominated lake ecosystems of the Late Cretaceous Fort Crittenden Formation, southeastern Arizona

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Facies of the Late Cretaceous Fort Crittenden Formation reflect the terrestrial response to changing paleoclimate and tectonics during the onset of ice house conditions within the western interior of the U.S. If uplift enhances monsoonal circulation then the lacustrine strata should reflect balanced to over−filled conditions and nutrient−stimulated productivity. Stacked sequences of beach, wetland, and deep lake deposits suggest multiple episodes of lake expansion and contraction in response to either climate or tectonics. Unionid bivalves within beach, wetland and deep lake facies are consistent with a freshwater lake. High and low spired gastropods track facies changes from deep lake to wetland deposits. Mottled color, nodular textures and pseudoslickensides within wetland deposits are indicative of soil forming processes that occurred during the driest phases of wet/dry cycles. Preliminary interpretations of the stratigraphic framework support a freshwater environment indicating balanced to over−filled conditions. Organic carbon contents and the relative concentration of n−alkanes, branched and cyclic alkanes, and polycyclic aromatic hydrocarbons (PAHs) are facies controlled. The saturated hydrocarbon fraction is characterized by the presence of n−$C_{12}$ through n−$C_{39}$ alkanes, trace−level abundances of pristane and phytane, and a high relative abundance of branched and cyclic alkanes. Contributions of odd−chain length n−alkanes were derived from land plants and aquatic algae. The abundance of branched and cyclic alkanes points to a bacterially dominated lake ecosystem. Specific PAH compounds are indicative of a pyrogenic origin, and high abundances of PAHs indicate major forest and/or peat fires within the surrounding watershed. Humid and seasonal paleoclimate would enhance biomass build−up in the watershed. Periodic wildfires and landscape denudation results in a pyrolitic PAH signal within deep lake deposits. Enhanced fluxes of inorganic nutrients following denudation appear to have stimulated bacterial productivity.

Orbital Forcing of the Early Cretaceous Ocean − A Perspective from Mediterranean Tethys

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Work on pelagic Cretaceous deposits in the Italian Apennines with Premoli Silva, Erba, Herbert, Grippo and others recently culminated in a coherent and spectrally documented cyclostratigraphy for the pelagic Albian, and will provide a basis for oceanographic assessment. Normal coccolith−globigerinid limestones and marls are interbedded with red marls which despite their oxidation state lack ichnofauna and represent advection and sinking of warm, saline, and nutrient−depleted oceanic surface waters. Both facies record responses to the orbital variations: the precession (damaged by bioturbation), the obliquity (at intervals), and the 95−ka and 406−ka eccentricity rhythms and yield an for an Albian duration of 11.9+− 0.5 Ma. The precessional alternation of a marl bed with a limestone, in a ca. 8−cm couplet, reflects oscillations in coccolith productivity and redox conditions on the sea floor (evidenced in ichnofauna). These differences are modulated over the 95−ka scale by the short eccentricity rhythm, which drove redox oscillation to anoxia, recorded in cm−scale sapropels for about one fifth of the cycles. Inconstancy between correlative sections implies that half or more of the couplets initially contained sapropels, but lost many to succeeding scavengers. The 406−ka cycles are less distinct, fractal repetions of the 95−ka cycles. Similar cycles pervade the Barremian, Aptian and Cenomanian. Those preceding both OAE−1A (the Selli sapropel) and OAE2 (the Bonarelli sapropel) are radiolarian cherts, suggesting that at these times the development of anoxic sulfurets in the oxycline had reached dimensions in space and time that allowed them to trap that scarcest of nutrients, iron, increasing fertility of overlying waters. The precessional cycle must be related to the alternation of highly seasonal perihelial summers with the damped seasonality of perihelial winters; the location between supercontinents suggests that the waxing and waning of monsoonal regimes must was important in eccentricity forcing; but the phase relations remain to be clarified. Abundance of soot in the sapropels (and in many other Albian deposits) suggests an abundance of fires, and the possibility of higher atmospheric oxygen content. These regimes ended with the widening of Tethys and the high sea level stands attained in the Turonian.

Water Mass Dynamics of the Western Interior Seaway based on Planktic Foraminiferal Porosity

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Modern studies support the hypothesis that shell porosity in planktic foraminifera reflect the temperature and salinity of the water in which they grow. Foraminifera construct more porous shells in warmer waters and less saline waters. Bijma et al. (1990) found shells grown in waters of 28°C were up to 2.8 times as porous as those grown at 19.5°C. They also found that shells grown at the same temperature but different salinities were 1.3 to 1.7 times more porous in the less saline waters. Modern planktic foraminifera are less diverse at lower salinities and do not inhabit modern waters Application of the planktic foraminiferal porosity method to the mid−Cretaceous has produced promising results. Specimens of the widely distributed mid−Cretaceous species Hedbergella delrioensis have been temporally studied through several sections and spatially studied along time−lines from many geographic localities across the Greenhorn Seaway. Stratigraphic studies show that porosity increases from the upper Cenomanian Metoicoceras mosbyense Zone into the lower Turonian Watinoceras Zone. The porosity increase is coincident with previously proposed sea−level rise. The porosity increase is interpreted as an increase in the influence of warm water that entered from the Tethyan Ocean. Geographic studies along time−lines reveal high porosities in the central seaway, with porosity decreasing shoreward and northward. The distributions are interpreted as a stratified seaway, consisting of a warm central near−surface water underlain by deeper waters that surfaced shoreward and northward. As sea−level rose the warmer central core expanded north and shoreward. If porosities are used as relative density proxy data, contour maps of porosity can be used to reconstruct geostrophic flow.

On the Impact of Milankovitch forcing on the sedimentary record of the Western Interior Seaway

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A multidisciplinary study of the late Cenomanian − early Turonian strata of the late Cretaceous Western Interior Seaway of North America explored possible mechanisms for the formation of cyclic bedding sequences. The Bridge Creek interval of the Greenhorn Formation shows well developed cyclic bedding in carbonate facies. Using reasonable estimates of rates of sedimentation, the limestone−marl couplets show periodicities similar to those expected from changes in Earth orbital parameters.

We investigated the sensitivity of the climate and sedimentary system to changes in one of the Earth's orbital parameters, the precession of the equinoxes, using numerical climate modeling (GCM−modeling). The ellipticity of the Earth's orbit was set at 0.05. We performed a month−by−month analysis of a suite of sensitivity tests simulating one complete precession cycle (four orbital setups). The varying insolation is reflected as changes in surface temperature, precipitation, snow cover, surface runoff and the rate of infiltration of water into the groundwater system. The simulations imply that the bedding couplets are the result of a varying supply of terrigenous material from the basin margin, diluting a more constant pelagic carbonate flux during the wetter parts of the Greenhorn cycles. Pure carbonate sedimentation dominated during the drier periods. The supply of terrigenous material was primarily controlled by mechanical erosion of the drainage basins in the highlands to the west of the seaway. The erosion of detrital sediment should be a function of surface runoff. It might be anticipated that the precessional signal seen in the sediments would reflect an increase and peak in surface runoff when perihelion coincides with the northern hemisphere summer solstice. However, the model predicts high surface runoff in summer during all orbital configurations except when perihelion coincides with northern hemisphere winter. The runoff peak results from intense convective summer storms. Instead of being the result of a spike of surface runoff at one extreme orbital configuration, the precession signal is produced by the elimination of the high summer runoff when aphelion occurs during northern hemisphere summer.

# Early Cretaceous platform drowning events along the northern Tethyan margin

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During the early Cretaceous, the carbonate platform attached to the northern Tethyan margin experienced a series of platform drowning episodes, which can be widely traced. The five episodes recognized cover the early Valanginian to early Hauterivian (D1), middle Hauterivian (D2), late Hauterivian to early Barremian (D3), early to early late Aptian (D4), and late Aptian to early Albian (D5). The particular sensitivity towards drowning in this platform system was probably related to its marginal paleoposition (ca. 30 degree N) with regard to reef growth, to its attachment to the European continent (a periodic source of reef−unfriendly weathering products), as well as to prevailing paleoceanographic conditions (sea−level change, upwelling intensity, presence or absence of connections to the boreal realm).

Drowning episodes are usually preceded by changes in carbonate production from a chlorozoan to a foramol mode, with important increases in accumulation rates. The drowning episodes themselves are documented by erosional surfaces and/or by the formation of strongly condensed beds rich in coarse sand, glauconite, phosphate, and biosilica. The presence of ammonites is a key to their dating.

If resolvable, the onset of drowning appears to be diachronous, and its evolution is by onlap onto the platform (D1, D4). Termination of drowning appears in all cases synchronous. Drowning episodes D1, D4, and D5 are correlated to positive excursions in the delta C−13 record, albeit with a slight diachronity in their onsets (drowning episodes lead the delta C−13 record), whereas episode D2 correlates to a negative excursion and episode D3 to a long and steady increase in delta C−13 values. This suggests that no uniform mechanism can be assumed for all five episodes but that each episode needs to be examined in its own context. An important element in all episodes is the change in weathering style and intensity in the continental hinterland, which profoundly affected detrital and nutrient fluxes.

Investigations of enhanced organic matter burial during the Cenomanian/Turonian boundary event and the related positive carbon−isotope excursion: implications of the OAE 2 for the global carbon cycle?

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The Cenomanian/Turonian (C/T) boundary event is the most prominent of the Cretaceous oceanic anoxic events (OAEs), characterized by a strong faunal crisis and a globally observed positive carbon−isotope excursion expressed in both carbonate and organic matter. To investigate the causes and consequences of this enhanced organic carbon burial event, the European C/T−net has chosen the C/T−OAE (OAE2) for a multidisciplinary research project focusing on C/T−sections in SE−England (Eastbourne), Morocco (Tarfaya Basin) and in Italy (Gubbio). The mid−Cretaceous period was characterized by the coincidence of intensified volcanism and oceanic crust production, a peak sea−level highstand and high paleotemperatures. Assuming that the increase in the atmospheric $CO_2$ concentration as the result of volcanic outgassing was the main cause for the Cretaceous "Greenhouse" climate, could the sequestration of organic carbon in the course of the OAE2 have provided a feed−back mechanism in the global carbon cycle to compensate for this? Corroborating evidence is provided by investigations of the carbon−isotope excursion from C/T−boundary sections offshore NW−Africa within the Proto−North Atlantic Ocean, based on $\delta^{13}C$ measurements on specific compounds derived from terrestrial leaves and marine phytoplankton.

Target sites for biomarker related investigations by the C/T−net are black shale−bearing sections in Morocco (Tarfaya), the South Atlantic (DSDP site 530) and Italy (Gubbio), where a core was drilled and sampled in high resolution by the entire network. The C/T−boundary interval is represented by the Livello Bonarelli, a one meter−thick regionally traceable band of carbonate−free black shales. Samples were selected for biomarker analysis and biomarker specific $\delta^{13}C$ measurements with isotope ratio monitoring−GC−MS. Investigations of free biomarkers confirm that the black shales are still immature and the organic matter is mainly of marine, phytoplanktonic origin. Isorenieratane, a molecular fossil specific for certain green sulfur bacteria and indicative for photic zone anoxia, was not found. This is in contrast to C/T−sites consisting mainly of black shales from the southern Proto−North Atlantic (i.e.: DSDP sites 367 144 or Tarfaya Basin), where sulfur−bound isorenieratane is abundantly present before and during the OAE2. Preliminary results indicate that the $\delta^{13}C$ excursion measured for specific phytoplanktonic biomarkers at Gubbio is surprisingly small compared to the isotopic excursion (up to 6 ‰) in the southern Proto−North Atlantic. The observed difference may be caused by a larger increase in overall primary productivity in the southern part of the Proto−North Atlantic compared to the Gubbio region during the C/T−OAE. This could imply that the Gubbio site mainly records the effect of enhanced organic carbon burial during the OAE2 on the global carbon reservoir stripped of additional local effects.

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Middle Turonian black shale deposition within the Western Interior Basin (U.S.A.) − an integrated model

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A basin−wide study on the paleoenvironmental controls on the formation of the Middle Turonian Carlile Shale and time−equivalent black shales was carried out utilizing an east−west transect through the Western Interior Basin (WIB). In the central part of the basin, three major black shale bearing−sequences are recorded during Albian to Santonian time related to long−term sea−level fluctuations. During transgressions, an epicontinental seaway extended meridional from northern Canada to the Gulf of Mexico. Perpendicular to the elongated axis of the seaway, our transect extends over approximately 1800 kilometers from Iowa to Utah and is based on seven cores. The Amoco Rebecca Bounds core located in the central WIB (Kansas) and the U.S.G.S. Portland core at a more proximal setting (Colorado) were chosen for high−resolution investigations of biomarkers and stable isotopes (bulk kerogen and carbonate). The investigation of sedimentary facies was carried out by screening samples from all sites for the amount and maturity of organic matter, analysis of the element−spectrum, and the main mineral compounds.

At the Bounds core locality, the reference section for the transect, the lowermost Fairport Member of the Carlile Shale consists mainly of laminated marlstones, deposited under oxygen−depleted conditions. The organic matter is immature and predominantly of marine origin, but a strong freshwater influence is indicated by biomarkers and $^{18}$O−data. The silty shales of the overlying Blue Hill Shale Member represent a transition to shallower water in a still oxygen−deficient setting, but with an increased influx of terrigenous organic matter. The long−term development of the Carlile Shale is linked to a continuous third−order regression modulated by sea−level fluctuations of fourth− and higher order, enabling subdivision into sub−members and small−scale cycles. Those are developed in the Fairport and Blue Hill Members and are expressed by variations in lithology and geochemistry. These cycles can be correlated to the Portland site, where the Carlile Shale interval is more condensed and incomplete. The small−scale cycles observed at both locations are best explained by high−order trans− and regressions. A paleoceanographic model for black shale deposition in the WIB is proposed, combining the sea−level history with constraints from the basin's morphology and salinity−proxies. It is primarily based on the different contributions of the two main water−masses in the WIB controlling spatial variations in bioproductivity and stratification patterns. Each transgression caused a renewed incursion of both water−masses into the basin, but to a different extent depending on the transgression's magnitude. At Fairport−time, the Portland location was more influenced by the fresher, cooler waters entering the WIB from the north than the Bounds site, which was dominated by a more saline, southern−derived water body. During the deposition of the Blue Hill Member, the morphological sill at the basin's southern aperture blocked these waters more or less completely from entering, resulting in dominance of the cooler, northern water−mass.

Late Cretaceous variations in d18O of precipitation and d13C of organic material over North America and their paleoenvironmental interpretations

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$\delta^{18}O$ and $\delta^{13}C$ ratios of vertebrate tooth enamel are related to those of ingested water and food, respectively. Because apatite in tooth enamel is resistant to diagenetic alteration, $\delta^{18}O$ and $\delta^{13}C$ of fossil tooth enamel can be used to investigate terrestrial environments of the past.

In this study, tooth enamel from theropod dinosaurs was analyzed from four North American localities in order to reconstruct patterns in $\delta^{18}O$ of precipitation during the Cretaceous. These sites include Big Bend, Texas (~30N), Alberta and Montana (~45−48N), and Alaska (~75N), and are all late Campanian/early Maastrictian in age. In addition, oxygen isotope data from scales of co−existing fish can be used in combination with the theropod data to estimate mean annual temperature (MAT) at each locality during the Cretaceous. In general, absolute $\delta^{18}O$ values were higher, and this implies that the atmosphere was able to hold more water vapor at that time. A smaller range in $\delta^{18}O$ values implies that less moisture was lost from air masses as they underwent latitudinal transport relative to the present. MATs were also higher at all localities, especially in polar regions. Both inferences are consistent with warmer global temperatures and shallower latitudinal temperature gradients inferred from marine isotope records and from fossil leaf assemblages.

In addition to theropod dinosaurs, tooth enamel was also sampled from herbivorous dinosaurs in order to estimate $\delta^{13}C$ of plants over North America. Sampled localites include Baja, Mexico, Big Bend, Texas, Montana, North Dakota, and Alaska. In four cases it was possible to collect samples from two coexisting herbivorous dinosaurs, and significant differences in average $\delta^{13}C$ were common between them. Such differences provide the first geochemical evidence for ecological niche partitioning between herbivorous dinosaurs.

Average $\delta^{13}C$ for a single type of dinosaur (hadrosaurs) also varied extensively between localities and indicates that varying environmental conditions and/or differences in local plant communities can strongly influence $\delta^{13}C$ of organic matter. This observation indicates that caution is needed when using $\delta^{13}C$ of organic matter as a chemostratigraphic marker in terrestrial settings, as variations in $\delta^{13}C$ may be due to local rather than global factors.

Cenomanian sea−levels and climate: evidence from SE India and NW Europe.

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The Cenomanian succession of the Cauvery Basin, SE India contains an expanded succession of coastal plain deposits which can be dated with precision from the use of cosmopolitan ammonite taxa and thus correlated accurately to marine successions elsewhere. The succession includes palaeosols, fluvial/tidal channels, and offshore sands which provide detailed evidence of sea−level changes. Using high−resolution biostratigraphy it is possible to correlate 11 individual sequences to Europe, 8000km distant. These sequences coincide precisely with the 400 kyr long eccentricity cycle.

In the Mid Cenomanian of NW Europe a short−lived cold event is documented by d18O data (bulk chalks and brachiopods) with a heavy shift of nearly 1.5 ppt, The event is precisely coincident with a rapid sea−level fall of about 25m on the Indian coastal plain which can be identified globally from the use of high−resolution ammonite biostratigraphy (mid Cunningtoniceras inerme Zone, 70ka duration). Orbital tuning of the conspicuously rhythmic succession by time series analysis of greyscale reflectance data provides evidence that the event occurs during a time of maximum eccentricity, characterised by increased contrast between dark marls and light limestones. The cold event represents a cooling of shelf bottom waters of about 5 degrees centigrade during a long eccentricity (400kyr) maximum, and is associated with a brief (c 15 kyr) southerly incursion of a colder water boreal fauna, and the lowest of two global positive excursions of d13C with a heavy shift of 0.7 ppt. Both the rapidity and magnitude of the sea−level fall and cooling are suggestive of glacioeustatic control.

Quantifying Precipitation Flux Changes of the mid−Cretaceous (Albian) Greenhouse World: Isotope Mass Balance Approach Constrained by Sphaerosiderite Oxygen Isotope Composition

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Spherulitic siderites are ubiquitous in ancient hydric/wetland paleosols that are widespread over coastal plains of the North American Cretaceous Western Interior Basin (KWIB). The oxygen isotopic of sphaerosiderite records that of paleogroundwaters, and thus serves as a proxy of precipitation oxygen isotopic composition.

Albian sphaerosiderites sampled from paleosols along the coastal plains of the KWIB exhibit a progressive depletion in oxygen isotopic composition from − 4 per mil at 34° N to −16 per mil at 75° N paleolatitude. The sphaerosiderite oxygen isotope composition has been used to constrain an isotope mass balance model of precipitation isotope composition and to quantify precipitation and evaporation fluxes along the KWIB.

Our modeling indicates that Albian precipitation fluxes were 38 to 53 % higher than present day fluxes. Likewise, evaporation fluxes are estimated to be 76 to 96 % higher than present day fluxes. While humid belts are wetter, the dry belts are drier. Precipitation rates exceeded 3500 mm/yr between 45° to 60° N paleolatitude, and could have been as high as 6000 mm/yr at 55° N.

Our estimates are consistent with geologic evidence such as the widespread distribution at high latitudes of paleosols that require high precipitation rates (e.g., laterites, ferralsols, plinthosols); extensive boulder to gravel conglomerates deposits in the Dakota Formation in Iowa and Nebraska; and widespread coal deposits at high latitudes.

Our model results differ from climate model results (e.g. GENESIS) in that equatorial precipitation rates are lower than those estimated by climate models, while mid to high latitude estimates are significantly higher and of equal or larger magnitude than those modeled for equatorial regions. Our estimates imply that atmospheric heat transport must have been significantly higher during the mid−Cretaceous (Albian) and can account for "missing" poleward heat transport during the mid−Cretaceous.

Large perturbation in the global carbon cycle preceding oceanic anoxic event 1b (Pacquier)

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Oceanic anoxic events (OEAs) have become a major source of discussion over the past decade mainly with the success of deep−time drilling from the ODP. During the drilling of Blake Nose (ODP Leg 171B), mid−Cretaceous sediments were recovered, and OAE 1b (Lower Albian) was identified with exceptional foraminifera preservation. Subsequent studies on this time interval revealed that during the black shale interval (~143 mbsf), oxygen−isotope ratios between benthic and planktic species diverged leading Erbacher et al. (2000, Nature 409:325−27) to attribute this to increased water column thermal stratification. The effect on carbon−isotope ratios was minor. Erbacher et al. thus concluded that the formation of the OAE 1b black shale could have involved similar processes as those leading to the formation of Quaternary sapropels.

Upon a closer inspection of colour photographs of Core 1049C−12X, we noted that ~2 m prior to the black shale interval studied by Erbacher et al. there was a major change in sediment colour cycles from alternating red and white to white and then grey. To determine whether this colour change had any paleoceanographic significance we requested samples every 10cm through all 6 cores (~8.5m). Although most foraminiferal studies use 10cc, we requested 1cc in order to obtain as high a resolution as we could while still obtaining enough foraminifera for isotopic analysis. All samples were processed using normal procedures and split into three fractions (150μm).

Stable−isotope analyses were first conducted on the bulk 63−150μm−fraction, predominantly consisting of juvenile and/or small planktonic foraminifera, and this revealed a large (2−2.5‰), rapid negative shift in $\delta^{13}C$ coinciding exactly with the interval of colour change from white to grey (~145.3m). Subsequently, the interval was re−sampled every 1 cm and monospecific assemblages of planktonic (*Hedbergella trocoidea*) and benthic (*Gyroidinoides infracretaceous*) foraminifera were picked and analysed. All records have shown a similar isotopic excursion across the white−grey interval. Given the published sedimentation rate for this core (Ogg Röhl 1999, Eos 80:F491−92), the excursion would have occurred during 5kyr or less.

Although the $\delta^{13}C$ of *H. trocoidea* and *G. infracretaceous* changed simultaneously, the magnitude of the initial shift was different: 1.5‰ and 1.9‰ respectively. The bulk 63−150μm−fraction $\delta^{13}C$ shifted slightly later (by one sample) in the record, and with a greater magnitude (>2‰). A similar pattern was discovered in the $\delta^{18}O$ record; the bulk 63−150μm−fraction shifted later and by ~1‰, *H. trocoidea* shifted by only 0.4‰ and *G. infracretaceous* by 0.7‰. What is most striking about the $\delta^{18}O$ record is that *H. trocoidea* returned to pre−excursion values whereas *G. infracretaceous* remained at post−excursion values: the difference between planktic and benthic species prior to the excursion was 1‰, after the excursion it was only ~0.16‰. These isotopic patterns would suggest that diagenesis and bioturbation had only a minor effect on the shape of the isotopic signals and that a major perturbation of the global carbon cycle must have occurred prior to the *sensu stricto* black shale of OAE1b in the Blake Nose ODP core. At present, a massive dissociation of continental margin methane gas hydrates is the only explanation for the magnitude and abruptness of the carbon isotopic shift, although such an explanation would require further corroborating evidence.

The Late Cretaceous Sea−level Curves

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In any comparison between the changes of sea−level in two regions, one has to distinguish two different aspects: (1) the dates of the highest and lowest sea−levels, i,e., the peaks of transgression and the troughs of regression; in EXXON terms, the time of eustatic stillstand in the highstand systems tract and the lowstand wedge in the lowstand systems tract; and (2) the extent of transgressions and regressions. The first is largely or entirely controlled by eustasy; the second commonly has a strong local tectonic factor.

Aspect 1. Eustatic control means that one can recognize quite modest sea−level lows in both North America and Europe, e.g., Rouen no. 1 Hardground in the Middle Cenomanian of Normandy is represented by the erosion surface beneath the Thatcher Limestone in Colorado. Similarly, the Campanian−Maastrichtian boundary in the Western Interior can be fixed by its distance above the eustatic high in the Bearpaw Shale in Montana.

Aspect 2. The general fall in sea−level in Wyoming−Montana−Alberta during the Late Campanian−Early Maastrichtian was caused by Laramide uplift. The fall in sea−level in this region of North America coincides with some of the highest Cretaceous sea−levels in northwest Europe when the sea transgressed on to older rocks in Ireland, Belgium and Sweden. At the same time the deepest water Cretaceous facies were being deposited in northern Mississippi and Tennessee against the south−western flank of the Appalachians.

Cretaceous terrestrial paleoenvironments of northeastern Asia suggested from carbon isotope stratigraphy: increased atmospheric pCO2−induced climate

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Terrestrial organic carbon from Cenomanian − Turonian sequences in Hokkaido Island, Japan has retained an isotopic record of the response of terrestrial higher plants to the paleoenvironment, superimposed on carbon isotope ratio fluctuation of atmospheric $CO_2$. The stratigraphic record of organic carbon isotopic compositions from the Hokkaido sections has been correlated to the carbonate carbon isotope record from Europe and North America; however, considerable discrepancy in the long− term, time−stratigraphic pattern of these isotope ratio curves exists through the Middle−Upper Cenomanian and Lower Turonian. Contrary to the marine carbonate profiles from Europe and North America which show consistent, positive migration through the Upper Cenomanian, terrestrial organic carbon isotope values display a negative shift through the Upper Cenomanian followed by positive recovery in the Lower Turonian. Environmental pressures that only affected carbon isotope values of terrestrial organic carbon but not those of carbonate carbon are causal factors for this discrepancy. Variations in atmospheric temperature and humidity, and related conditions of carbon cycling in forests, may have acted as factors to shift isotope values of terrestrial organic carbon negatively. This causal relationship between climate and carbon isotope ratio fractionation is best explained when an increasing atmosperic $pCO_2$, which is suggested from a decoupling between isotope ratio curves of marine organic carbon and carbonate, is understood as a driving force for a climatic optimum during the Middle Cenomanian through Early Turonian.

Speculations on Circulation of the Cretaceous Ocean

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Circulation of the ocean reflects a long−term integration of the atmospheric circulation. Today the surface of the ocean is characterized by tropical−subtropical anticyclonic gyres and polar cyclonic gyres separated by frontal systems that are the origin of the ocean pycnocline. This surficial oceanic circulation system is driven by the winds. It is a clear reflection of the 3−cell per hemisphere atmospheric circulation system that exists but is characterized by high latitude variability in the form of Rossby waves separating the polar and intermediate cells. The surface circulation carries about 80% of the global ocean heat transport; the remainder is characterized by the thermohaline circulation system that today involves sinking of water at small high−latitude sources and broad slow upwelling throughout the tropics and equatorial regions.

The geologic record of the Cretaceous and early Cenozoic ocean does not reflect this pattern of circulation. There is little evidence for oceanic frontal systems although fronts do exist in shallower, narrow meridional seaways. Recent climate simulations for the Turonian suggest that atmospheric circulation in the Cretaceous may alternate seasonally between 3−cell and 2−cell systems. Today the stability of the 3−cell circulation is forced by ice in the high latitudes, which ensures polar high pressure systems throughout the year. The lack of polar ice in the Cretaceous and early Cenozoic results in an alternation between polar highs in the summer and lows in the winter. With such unstable atmospheric circulation, only the equatorial portions of the oceanic tropical−subtropical anticyclonic gyres would be well developed, with unstable boundaries characteristic of the polar regions. This would result in a less well developed oceanic pycnocline. Further, the lesser wind speeds of the Cretaceous, coupled with the more intense hydrologic cycle of a warmer Earth, might bring the wind−induced and evaporation/precipitation−induced ocean surface topography more nearly into balance, further destabilizing ocean circulation. With lesser pycnocline stability, and with warmer global temperatures, the ocean thermohaline circulation system might take on a larger role in global energy transport system.

Sedimentological and Geochemical Expressions of the Mid−Cretaceous OAE 1a in Pelagic and Coastal Settings: A Comparison

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The Early Aptian is referred to as a time of major perturbations in the ocean−atmosphere system, documented by the widespread deposition of organic carbon−rich shales in the world oceans, accompanying biological turnover and pronounced excursions in the carbon−isotope record. Even though these changes have been described in great detail from different pelagic and hemipelagic settings, few studies have been carried out focusing on shallow water environments and their responses to climatic and oceanographic disturbances during this time interval.

Mixed carbonate−siliciclastic coastal deposits of Early Aptian age from the Portuguese Algarve basin have been chosen as the near−shore archives to study from a sedimentological, geochemical and palynostratigraphic perspective. Carbon−isotope stratigraphies have been established for two sections based on bulk organic matter (OM) of terrestrial origin. The dominance of continent−derived plant material in the bulk OM fraction has been confirmed by optical studies, Rock−Eval pyrolysis and by comparison with the $\delta^{13}C$ signature of different types of fossilized land−plant particles. Both sections exhibit a very similar carbon−isotope pattern displaying a pronounced isotopic minimum (−27.8 ‰) followed by a prominent shift towards higher values (up to −19.4 ‰).

This terrestrial carbon−isotope record is compared with $\delta^{13}C_{org}$ data of marine origin, obtained from a stratigraphically well−constrained hemipelagic succession (Vocontian basin, SE France), representing the OAE 1a black shale. This distinct organic carbon−rich horizon corresponds to a stable interval in the $\delta^{13}C$ record (chemostratigraphic segment C5) within the step−like, negative−positive carbon−isotope shift occurring above polarity chron M0 in the NC6 nannofossil Zone and the lowermost Leupoldina cabri planktic foraminiferal Zone.

Remarkable similarities between the terrestrial and marine carbon−isotope records, in combination with the palynostratigraphic results, facilitate a detailed chemostratigraphic correlation from the basinal to the coastal realm and enable comparison of the sedimentary evolution in the different environments at a high−resolution.

In contrast to the hemipelagic succession, none of the studied coastal sections comprise an organic−rich layer. The basinal black shale horizon corresponds to a marked interval of siliciclastic shedding in the near−shore environment, documented by the occurrence of a ca. 10 m thick sequence of bedded silt− and sandstone and a pronounced drop in $CaCO_3$ content. These siliciclastics are overlaid by a 6 m thick package of peritidal carbonates, forming prominent banks in the clay− and marlstone−dominated sedimentary system. The deposition of the coastal succession took place during a transgressive depositional sequence following a major discontinuity of Early Bedoulian age.

The studied near−shore succession shows pronounced changes in the sedimentological pattern during deposition of OAE 1a. Whether these changes are controlled by short−term sea−level fluctuations and/or reflect variations in weathering conditions due to climatic disturbances during the Early Aptian has to be solved.

Orbitally forced black shale accumulation during Coniacian−Santonian times in the Ivory Coast Basin

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The accumulation of black shales in the Ivory Coast Basin (ICB) during Coniacian to Santonian times displays characteristic cycle patterns, which can be recognized based on the fluctuation of organic carbon content (TOC) and selected geochemical ratios (e.g. K/Al, Si/Al and Ti/Al). We constructed a floating orbital time scale for nanno−fossil zone CC 15 on the assumption that the cycle pattern is controlled by orbital forcing. The time scale allows to address accumulation rates for selected chemical elements which can be related to specific mineral phases. The timing of peak accumulation for these minerals within the orbital cycles indicates detrital sediment input from at least two distinct source areas, i.e. kaolinite and smectite input from tropical regions, which coincides with peak TOC accumulation, and quartz and illite input from arid source regions. A comparison of our results with climate reconstructions for the Upper Cretaceous suggest that the detrital sediment supply and the related black shale accumulation at the ICB is controlled by the precession forced migration of the inner tropic convergence zone (ITC) across western Africa. A northern paleo−position of the ITC allowed the transport of quartz and illite from a proto−Namib desert to the ICB via the SE−trade wind system and resulted in low accumulation rates for TOC. A southern position of the ITC kept the ICB under the influence of tropical condition, which resulted in extensive continental run−off, and locally developed an estuarine circulation pattern. The supply of nutrients to the ICB related to the later climate situation fostered the accumulation of black shales.

Benthic foraminiferal extinctions across mid Cretaceous OAES: Evolutionary turn−over or rock record bias?

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We examined records of well preserved benthic foraminiferal assemblages across Cretaceous oceanic anoxic events OAE 1a−c and OAE2 from bathyal and abyssal DSDP/ODP Sites (Sites 1049, 1052, Blake Nose, Site 551, Goban Spur, Site 603, and Site 641) and from bathyal to neritic onshore sections in Morocco, Spain, Southeast France and North Germany. Diversity, taxonomic composition and preservation potential of benthic foraminiferal assemblages at shelf localities are strongly influenced by changes in paleo−water depth, particularly at times of major sea−level change. Thus, most of the observed faunal changes at shelf sites express environmental change and taphonomic bias, rather than true extinction and radiation events. We found no evidence for a major benthic foraminiferal turn−over during OAE1 and OAE2 both at middle and upper bathyal sites. Most taxa recorded at these locations have stratigraphic ranges extending across oceanic anoxic events. The changes in biofacies recorded across the OAEs coincide with changes in hydrography and sedimentological facies. By contrast, abyssal benthic foraminifers underwent a marked radiation after the late Cenomanian OAE−2 in the Atlantic Ocean and the Mediterranean Tethys, which may be triggered by a general change towards better oxygenated deep−wate

Cretaceous Marine d18O Cooling Excursions: An Ice Sheet for Every Event?

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The concept of long−term stability and equitability of the Cretaceous greenhouse climate is giving way to recognition of much greater variability in global temperatures on both short and long time scales as a result of increasingly detailed oxygen isotope paleotemperature studies. Recognition of short−term positive $\delta^{18}O$ shifts combined with apparent 3rd order sea level fluctuations in several intervals has revitalized the debate about whether or not continental ice sheets existed at polar latitudes during the Cretaceous. Correlation between 0.5 to 1.5 per mil positive shifts in their bulk carbonate $\delta^{18}O$ curve with lowstands in the EXXON sea level curve during the middle Cenomanian, late Turonian and early Santonian (~84−85 Ma) was used by Stoll and Schrag (2000) to support glacial forcing. Similarly, Miller et al. (1999) argued for glacio−eustasy during the lower Maastrichtian (~ 69−71 Ma) to explain correlation between an unconformity in the New Jersey margin, positive $\delta^{18}O$ shifts at several deep−sea sites, and cool high latitude SSTs during the early Maastrichtian.

Without direct geological evidence of Cretaceous continental glaciation, confirmation of the existence of Cretaceous ice−sheets requires demonstration that the oxygen isotopic shifts and lowstand events are globally synchronous and consistently correlated and that ice buildup is reasonable. The oxygen isotope record from ODP Site 1050 on Blake Nose (subtropical North Atlantic) can be used to test for glacial forcing within the late Aptian−early Albian, late Albian−early Coniacian, and mid−Campanian−late Maastrichtian. The middle bathyal benthic foraminifer $\delta^{18}O$ record at Site 1050 contains six short−term, positive shifts that range from 0.3 to 1.0 per mil, but none are likely to be related to polar ice sheets because (1) the benthic $\delta^{18}O$ shifts are not accompanied by positive shifts in co−occurring planktonic foraminifera; (2) the shifts do not correlate with recognized sea−level lowstands; (3) synchronous positive $\delta^{18}O$ shifts do not occur at other deep sea sites; and (4) bottom water temperatures and high latitude SSTs at the time of the excursions were generally too warm to allow for a positive snow balance at polar latitudes. Until reasons are found for why only selected Cretaceous positive $\delta^{18}O$ excursions were glacially forced, we argue that non−glacial explanations for short−term variations are favored.

Terrestrial Linkages between the Atmosphere and Biosphere: Cretaceous Applications

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Terrestrial plants play a unique role in the Earth System, in that they are in constant and direct contact with the atmosphere, as they metabolize carbon dioxide in order to synthesize their own tissues. Because the carbon of the paleoatmosphere is preserved as plant fossil tissue through most of the Phanerozoic, I have worked to quantitatively assess the relative contribution of factors internal to plants, as well as changing environmental conditions, to plant tissue $\delta^{13}C$ value. I use these relationships to reconstruct environmental information for the Cretaceous from plant fossil isotopic analyses. Land plants sample the isotopic composition of atmospheric $CO_2$ directly during photosynthesis. For C3 plants, which dominated Cretaceous ecosystems, isotopic fractionation during carbon assimilation is influenced by the discrimination due to differential diffusion of $^{12}CO_2$ versus $^{13}CO_2$ in air, discrimination imparted by the primary carbon fixation enzyme, and ecophysiological factors that balance carbon gain with water loss in the leaf . In an analysis of a large data set (519 published $\delta^{13}C_{plant}$ measurements on 176 C3 species) Arens, et al. (2000) showed that the relationship between the $\delta^{13}C$ value of plant tissue and atmospheric $CO_2$ is linear and significant ($r^2 = 0.91$ for the full data set). Using a subset of these data, Arens, et al. (2000) proposed an empirically−derived relationship [$\delta^{13}C_{atmosphere} = (\delta^{13}C_{plant} + 18.67)/ 1.10$] that could be used to estimate $\delta^{13}C$ of atmospheric $CO_2$ from preserved terrestrial plant material. In actualistic tests to verify the predictive ability of this method, Arens, et al. (2000) showed that for most mesic environments, the relationship predicted both ancient and modern atmospheric $\delta^{13}C$ values within the defined confidence interval. In addition, this finding has been confirmed through the analysis of modern accumulating sediments from several sites, all of which yielded an atmospheric prediction within 1.0‰ of the true modern value. I have reconstructed the $\delta^{13}C$ of Cretaceous atmosphere using $\delta^{13}C$ values of isolated cuticle (a component unique to land plants) from two regions: three localities in the Cordillera Oriental of the Colombian Andes, South America and at the United Clay Mine locality of the Arundel Formation of Western Maryland, North America. Both terrestrial records show a ~5‰ negative excursion during the Aptian of the Early Cretaceous that correlates with excursion of lesser magnitude observed in marine records. In presentation, I will evaluate potential causes of this excursion, and discuss its possible relationship to widespread oceanic anoxia recognized during the Aptian.

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Flip from dysoxic to oxic state of world oceans during Late Cretaceous

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The Cretaceous differs from the other periods of the Mesozoic being a time of major plate tectonic, paleoceanographic, biologic and paleoclimatic changes. It is also economically important, as it contains the highest percentage of source rocks for hydrocarbon generation from the whole Phanerozoic. Most previous research has been devoted to explaining the major "anoxic" events in the early Aptian and at the Cenomanian−Turonian boundary. These events marked by positive carbon−isotope excursion have been attributed to various earth processes − such as increased volcanic activity when carbon dioxide led to global warming, changes in bioproductivity, ocean circulation and tectonics. Less attention was paid to the time between these events also characteristic by deposition of dark grey, to black shales. Deposition of such shales in the North Atlantic ocean basin was initiated during Valanginian and continued to the late Cenomanian. A major change in the character of deep sea deposits in the North Atlantic occured after deposition of the Bonarelli horizon (Cenomanian−Turonian boundary), with the dysoxic depositional environment being rapidly replaced by a highly oxic environment. This change is indicated by zeolitic red clays, lack of organic carbon and very low sedimentation rates in abyssal basins. Such deposition continued into the Paleocene in the North Atlantic, but was of shorter duration in parts of the eastern Tethys. The change to oxic ocean state is recognizeble not only in the abysal deep−sea deposits, but also on continental slopes and rises, where reddish marls, like Scaglia Rossa in Italy, or Puchovke marls in Slovakia, were deposited above the CCD. Why was there this change to a more oxic state of the world oceans? Does it indicate major changes in the bioproductivity of the oceans, ocean chemistry, oxygen, circulation, or another, unrecognized change in the Earth Systems?

To answer some of these questions the International Geologic Correlation Program approved in early 2002 the new project: IGCP #463, "Upper Cretaceous oceanic red beds: Response to ocean/climate global change." Although, several different hypothesis have been advanced to explain the major change in the oceans during the late Cretaceous and will be discussed during the Workshop, none have withstood close scrutiny. Involvement of the broad scientific comunity in IGCP # 463 might lead to an understanding of the causes of such major change in global oceans represented by the flip from dysoxic to oxic ocean in the late Cretaceous.

Campanian isotope events, sea level and climate change

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New Campanian stable isotope data from a thick Tethyan Campanian − basal Maastrichtian pelagic − hemipelagic section at El Kef, Tunisia, and a Boreal Santonian − Campanian chalk succession at Sulukapy, Kazakhstan are presented. Carbon, oxygen and strontium isotope data from the Trunch borehole in eastern England are reviewed in the light of a detailed lithostratigraphy, and some new stable isotope data are reported. Carbon isotope data are compared to published curves from England, Germany and France.

The general shapes of the Campanian carbon isotope curves exhibit remarkable similarities in all areas. A positive $\delta^{13}C$ excursion spans the Santonian / Campanian boundary (~83.7 Ma), a second positive carbon isotope event occurs in the mid−Campanian (~78.7 Ma), and a negative excursion characterises the upper Campanian (~74.8 Ma). These events, together with smaller peaks, troughs and inflection points in the isotope profiles enable precise inter−regional correlations that are consistent with nannofossil data. Major shifts in $\delta^{13}C$ profiles coincide with changes in eustatic sea−level, and provide robust chronostratigraphic trends that offer potential for bed−scale inter−continental correlation independent of biostratigraphy. Relatively stable $\delta^{13}C$ values in the lower Campanian and their long−term fall through the upper Campanian reflect high and then falling eustatic sea−levels, and increased carbonate production on late Campanian platforms and in epicontinental seas. Short−term (~600 kyr) positive excursions record greater organic productivity and/or organic matter preservation and decreased carbonate fluxes during periods of rapid sea−level rise and the drowning of carbonate platforms. Excursions were terminated by falling nutrient supply and increased carbonate fluxes associated with epicontinental sea expansion and renewed carbonate platform growth during the late transgression and highstand. Negative excursions are linked principally to reworking of marine and terrestrial organic matter during rapid sea−level fall. Oxygen isotopes exhibit a wide range of values in the different study sections. Stratigraphic trends in Tunisia are inconsistent with other areas, indicating a substantial local diagenetic overprint. However, $\delta^{13}C$ shows no covariance with $\delta^{18}O$, confirming that the carbon isotopes preserve primary stratigraphic trends. Rising $\delta^{18}O$ values through the Campanian in the other sections reflect falling sea−surface temperatures accompanying Late Cretaceous global cooling. Gradient changes in the isotope profiles and short−term peaks and troughs may reflect short−term climate events. Cooling was most rapid during the early to mid−Campanian accompanying eustatic sea−level rise, but slowed and may even have reversed during the late Campanian regression. Strontium isotopes record a remarkable linear increase through the Campanian and, although insensitive to short−term sea−level change, provide an independent means of dating and correlation. The combination of sedimentological, biostratigraphic and chemostratigraphic data provides a powerful tool for constraining Late Cretaceous environmental change.

The Cenomanian−Turonian Oceanic Anoxic Event: crystallizing the concept

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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−nineteen−seventies to the concept of Oceanic Anoxic Events. Such events, whatever their exact nature and cause, were hypothesized to foster 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 implicit 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. Although early stratigraphic compilations attributed black shales of this approximate age to either the late Cenomanian and/or the early Turonian, increased stratigraphic resolution has demonstrated a remarkable synchroneity of these characteristic deposits around and across the stage boundary. The advent of carbon−isotope stratigraphy in the nineteen eighties, with the recognition of a characteristic positive excursion related to excess global carbon burial, offered an independent means of high−resolution correlation on a global basis, independent of biostratigraphy. Recent carbon−isotope studies from England, Italy, Morocco and elsewhere now demonstrate that the stratigraphic position of Cenomanian−Turonian black shales, or of their most carbon−rich portions, is not fixed in exactly the same position with respect to 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. Hence, at these high levels of resolution, the "stratigraphic" concept of the Oceanic Anoxic Event breaks down. The event is thus more usefully defined with respect to the carbon−isotope excursion alone. Broadly coincident increases in bulk nitrogen−isotope ratios and total organic carbon over the interval of the carbon−isotope excursion suggest that in most, if not all localities enhanced productivity was a more important mechanism than was enhanced preservation for the generation of black shales during the Cenomanian−Turonian Oceanic Anoxic Event.

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Tropical environmental dynamics inferred from biotic dispersion patterns

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Changes in the environment have modified the ecological role of reef builders through geologic time, and major extinctions have reset evolutionary patterns. In Cretaceous reefs, the relative ecologic role of scleractinian corals and rudist bivalves shifted during the middle Cretaceous, and rudist bivalves took over as the dominant skeletal organisms for the remainder of the period.

In previous works related to Cretaceous reefs, species diversity of rudist bivalves was quantified, reef lines based on the distribution of the bivalves were established on plate reconstructions, and fluctuations in the reef lines were interpreted in terms of thermal changes attributed to ocean heat transport. A dynamic rather than stable environmental history was proposed for the tropics, and the role of large−scale disturbance in the evolution of tropical ecosystems was proposed. However, the role of bivalves as proxies for reefal conditions remains questionable, and the time periods of the Cretaceous for which hypotheses of biotic change were proposed were temporally and geographically variable across the globe.

In this work, the geographic locations of scleractinian coral species were plotted for the Caribbean and circum−Caribbean region for all stages of the Cretaceous. Species occurrences were noted for each stage and plotted on present−day mercator maps. Occurrences were grouped and transferred per five degrees paleolatitude to the 130, 95 and 80 my plate tectonic reconstructions. Number of occurrences, number of species, and number of paleolatitude increments comprised the observed data base used for statistical analyses of colonial corals.

Results of the statistically analyzed coral database, and comparison to rudist bivalve data and interpretations, include the following. 1. Coral data fill in the reef line for the earliest Cretaceous stages. 2. The geographic extent of the Caribbean reef line defined initially on rudist bivalves was conservative. Colonial corals expand the paleolatitudinal extent of the tropics and display temporal patterns of geographic expansion and contraction similar to those expressed previously by rudists. 3. Dispersion patterns for corals and rudists infer that the geographic extent of the Cretaceous tropics was greater than that of our present−day interglacial period. 4. Knowledge of the paleolatitudinal extent of the ancient tropics is essential for analyzing the role of the tropics in ocean and atmospheric heat transport.

The larger−scale focus of this investigation is to question the driving mechanism for evolution in the tropics. A first−order inquiry concentrates on dynamic environmental conditions as opposed to tropical stability, and subsequent investigations analyze the processes driving tropical evolution under greenhouse versus icehouse conditions. Paleobiological questions center on macroevolutionary factors involving both the environment and the ecological characteristics of the co−existence of the two groups, specifically, morphologic and taxonomic changes expressed during the critical mid−Cretaceous faunal transition.

High stress paleoceanographic conditions during the last 700 kyr of the Maastrichtian in the eastern Tethys (Tunisia, Egypt and Israel)

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At Elles, Tunisia, Milankovitch−scale cycles (20 kyr precession, 40 kyr obliquity, 100 kyr eccentricity) can be recognized in high−resolution carbon−13 and oxygen−18 ratios, Sr/Ca, mineralogical and magnetic susceptibility data in hemipelagic sediments that span the last 700 kyr of the Maastrichtian. Oxygen isotope data reveal three cool periods between 65.50−65.55 Ma (21.5−23.5 m), 65.26−65.33 Ma (8−11 m) and 65.04−65.12 Ma (1.5−4 m), and three warm periods between 65.33−65.38 Ma (12−16 m), 65.12−65.26 Ma (4−8 m) and 65.00−65.04 Ma (0−1.5 m). The cool periods are characterized by small surface−to−deep temperature gradients, reflecting an intensive mixing of the water column. The carbon isotope composition of planktic foraminifera indicates a continuous decrease in surface bioproductivity. Decreasing carbon−13 isotope values (the difference between the carbon isotopes of surface and bottom dwelling foraminifera), and the carbon isotope ratios of the planktic species at the onset of gradual warming at 65.50 Ma reflect a reduction in surface productivity as a result of decreased upwelling that accompanied global warming, and possibly increased atmospheric pCO2 related to Deccan Trap volcanism. Planktic foraminifera responded to the cooling episodes with a decreased species diversity, including a decrease in globotruncanid species (intermediate dwellers), followed by continuing low diversity or a further decrease during the maximum warming. Times of high stress, are indicated by low species diversity and blooms of the opportunistic species Guembelitria at warm−cool transition intervals. During the last 100 k.y. of the Maastrichtian rapid cooling is associated with accelerated species extinctions followed by the extinction of all tropical and subtropical species at the K−T boundary.

At Qreiya in Central Egypt, significantly higher stress environmental conditions, akin to those normally experienced during the K/T transition, are indicated by faunal and stable isotopic data during the late Maastrichtian (66.8−65.4 Ma). Central Egypt experienced a breakdown of the biologically mediated surface to bottom gradient of the 13C/12C ratio, with planktic foraminiferal species diversity reduced by more than 50%, and faunal assemblages dominated (75−90%) by the opportunistic disaster species Guembelitria cretacea. This prolonged breakdown in ocean primary productivity occurred during a time of global climate cooling, but seasonally warm, wet, tropical and subtropical conditions prevailed locally. A normal carbon isotope gradient was briefly re−established during the short climate warming and rising sea level between 65.4−65.2 Ma.

At Mishor Rotem in southern Israel, late Maastrichtian high−stress conditions are also indicated by very low species richness (30−35 species) and three Guembelitria blooms (coeval Egypt and Tunisia), accompanied by seasonally wet and dry periods. Most remarkably, these climatic changes are accompanied by deposition of three red clay layers interbedded in white chalk at the base and near the middle of the Plummerita hantkeninoides zone that spans the last 300 kyr of the Maastrichtian. These red layers contain spherules and major Pd and Pt anomalies (but only minor Ir) are present in two of them. An Ir anomaly is present in the K/T boundary red layer 1.2 m upsection. The origin of the spherules and Pd and Pt anomalies, and their relationship to the environmental changes are still unclear. However, the presence of three spherule layers in coeval stratigraphic positions in Mexico suggest major volcanic and/or impact events contributed to the global climatic changes of the last 300 kyr of the Maastrichtian.

Benthic paleoecology during mid−Cretaceous OAEs and in modern oxygen mimima: is the present the key to the past?

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Key environmental parameters influencing benthic communities are food and oxygen. The main source of food for oxygen minimum communities in modern ocean is carbon flux from surface primary production. Amount, composition of export production as well as transport and decay processes within the water column and at the sea floor are thus the main controls on the composition of the benthic community in the modern oceans. Consequently, the distribution record of benthic foraminifers in the modern ocean can be used to quantitatively reconstruct primary production and carbon flux. Trophic chains may have been signifcantly different during Jurassic and Cretaceous OAEs: the composition of primary producers may have been different (i.e. diatoms may have been a less important component in the food chain), transfer mechanisms of organic carbon to the deep−sea may have been fundamentally different in a warm saline ocean and benthic sources of organic carbon (i.e. chemosynthetic bacteria) may have played a more important role.

To decode the organic carbon flux and water mass oxygenation signals embedded in the fossil record of benthic foraminifera we thus have to consider processes on three different timescales. These timescales correspond to the duration of species (evolutionary, million of years), populations (paeloecological, thousands of years) and individuals (life histories). Life histories of benthic foraminifera in modern high carbon flux/oxygen minimum environments vary on time scales of days, seasons, or years, depending on the ecological niche, feeding strategy, reproduction cycle, and population dynamics of individual species. The short−term extreme with reproduction cycles and life histories in the range of days or weeks and extremely fluctuating high population densities is represented by phytodetritus exploiting species, whereas detritus feeders can live over several years in small populations, that are controlled by the available oxygen or food resources.

A comparsion of benthic foraminiferal communities from Jurassic, early Cretaceous and late Cretaceous OAEs and different types of modern oxygen minima shows, that the modern analogue may be applicable to the late Cretaceous OAE2 and OAE3, but significantly different life cycles and reproduction strategies may have prevailed during the Jurassic and Lower Cretaceous OAEs.

Mid−Cretaceous igneous events and geological responses: The devil is in the details

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Increased rates of volcanism associated with oceanic plateau formation and sea floor spreading in mid−Cretaceous time probably caused a variety of geological responses, including black shale episodes and changes in isotopic ratios of carbon, oxygen and strontium. However, small but possibly significant mismatches between radiometrically dated oceanic basalts and stratigraphically dated geological responses make it difficult to establish cause and effect relationships with certainty. In particular, radiometrically dated basalts from the Ontong Java and Manihiki Plateaus average 123 Ma, while the Selli black shale (OAE1a) and associated isotopic ratio anomalies occurred 2−3 m.y. later. Precise paleotemperature estimates are still needed for the Barremian−Early Albian interval to assess the potential effect of this huge volcanic episode on paleoclimate. 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, have been redated and with one exception now have radiometric ages of about 92−95 Ma. Thus, the case is considerably stronger, but not yet certain, that Caribbean Plateau volcanism contributed to the Bonarelli black shale episode (OAE2) and associated isotopic anomalies near the Cenomanian/Turonian boundary at 93.5 Ma. These new age 40Ar−39Ar whole rock age determinations are based on incremental heating experiments that, with one exception, produce Ar−recoil patterns from which only total fusion ages can be extracted. These 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.

A substantial amount of mid−Cretaceous and older oceanic crust, especially in the Pacific Basin has been subducted in the past 120 m.y. This has erased much of the potential evidence for the increased igneous activity from the geological record. Thus, there will always be unverifiable assumptions in any hypotheses that hope to explain the causes and effects of mid−Cretaceous events. More samples from the existing ocean floor record, which can be dated with increasingly precise radiometric and stratigraphic techniques, are clearly necessary to assess in more detail these mid−Cretaceous relationships. A significant part of the time allotted for this talk will be devoted to a group discussion of future IODP drilling and potential drill sites to address these issues.

Relative sea level history of the uppermost Cenomanian of southwestern Utah: evidence for Milankovitch−driven eustasy?

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Many aspects of Late Cretaceous eustasy, including timing, amplitudes, and forcing mechanisms, remain poorly understood. Recent studies suggest a possibility of Milankovitch forcing of the Cretaceous "greenhouse" eustasy (e.g. Plint, 1991; Fischer Hinnov, 2000; Gale et al., 2002), but stratigraphic data, which would exceed, in their temporal resolution, the constraints given by biostratigraphic zonation are extremely rare. The latest Cenomanian interval of the Western Interior Seaway, which was characterized by coexistence of climate−sensitive hemipelagic rhythmites (e.g. Gilbert, 1895; Fischer, 1980) and sea−level sensitive siliciclastics (Elder et al., 1994), and is suitable for high−resolution correlations (e.g. Elder, 1985, 1991), provides an excellent opportunity to improve our understanding of climate−ocean interactions during "greenhouse" times.

The remarkably complete stratigraphic record of the proximal part of the Sevier foredeep of southwestern Utah provided detailed information on relative sea level history of the latest Cenomanian interval of this part of the basin. A resulting genetic−stratigraphic framework, which differs from the existing stratigraphic concepts (e.g. Elder et al., 1994) in both stratigraphic resolution and interpreted along−dip genetic relationships, was correlated, in both outcrop and subsurface, with an offshore setting of Kaiparowits Plateau. A high−resolution stratigraphic framework, established for offshore strata by Elder (1985, 1991) and Elder et al. (1994), was further used to pin our data on relative sea level history to a detailed, Milankovitch−based time scale established recently for the Bridge Creek Limestone by Meyers et al. (2001). Temporal resolution of our stratigraphic data obtained by this method was at the order of tens of kyr (depending largely on uncertainties in the proximal−distal correlation in the nearshore parts of the basin).

According to our data, at least two orders of relative sea level (RSL) change are superimposed on the long−term relative sea level rise spanning the latest Cenomanian through mid or late Early Turonian (the corresponding transgressive trend culminated during the late P. flexuosum or early V. birchbyi Zones in southern Utah). The higher order of RSL change is represented by three cycles, in the latest Cenomanian Sciponoceras gracile Zone and the early part of Neoceradioceras juddii Zone. Their duration approximates 90−110, 50, and 110−160 kyr (from oldest to youngest). These RSL cycles include a minimum of 3, 2, and 2 sub−ordered units, respectively, which are attributable to short−term RSL changes. In most instances, these lowest−order units cannot be individually correlated with the hemipelagic setting. Their approximate durations were thus estimated using the simplistic assumption that each short−term cycle represents an equal increment of time. Resulting average durations range from 25 to 80 kyr. Since some short−term RSL cycles are likely to have remained unidentified by us, these estimates represent the maximum average duration of short−term RSL cycles in the interval of study.

Since tectonically−induced RSL changes of such extremely short time scales and hierarchical organization are not known from foreland settings, we propose that at least part of the interpreted RSL history is due to short−term eustatic oscillations. The estimated durations would be consistent with Milankovitch−related forcing. To test this hypothesis, we performed a series of numerical simulations and tested reproducibility of both the interpreted relative sea level curve (based on decompacted stratigraphic profiles) and the observed progradational patterns with Milankovitch−like eustatic forcing. The major patterns of the interpreted RSL curve and stratigraphy were reproduced using 22, 39, 95 and 413 kyr periods (adopted from spectral analyses of the Bridge Creek Limestone; Meyers et al., 2001) with 0.2−2.5, 2, 0.8−6, and 8 m of amplitude of eustatic change, respectively, superposed upon 35m/100kyr of linear rise (sum of subsidence and long−term eustatic rise). The same eustatic curve and clastic−input conditions, superimposed upon 20m/100 kyr of linear rise (simulating the assumed low−accommodation conditions in the Bridge Creek source area) can reproduce the 413 kyr maximum in Ti accumulation (proxy for detrital flux) documented from the latest Sciponoceras gracile Biozone of the Bridge Creek Limestone by Meyers et al. (2001). Similar results were obtained after exclusion of the obliquity (~39kyr) cycle from the synthetic eustasy. In contrast, obliquity−like eustasy alone failed to reproduce the observed stratigraphy.

In summary, the combination of genetic stratigraphy of the marginal part of the Western Interior Seaway with results of spectral analysis of the Bridge Creek Limestone (Meyers et al., 2001) and numerical stratigraphic modeling, suggests that Milankovitch−scale eustasy does not contradict stratigraphic observations from nearshore settings. In spite of "imperfections" in the relative timing of Cenomanian RSL changes in southwestern Utah and the Milankovitch cycles recorded in central Colorado, the study presented herein suggests that combined eccentricity/precession−driven eustasy is a possibility to consider when dealing with the "greenhouse" Cretaceous world (cf. Fischer Hinnov, 2000).

Cretaceous tectonic events and their influences on ocean circulation

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Prior to the Jurassic break−up of Gondwana, there was one global ocean, the Pacific Ocean. By the earliest Cretaceous, a circum−tropical seaway opened, extending from the Tethys region between Africa and Iberia into the Central Atlantic between North America and Africa. Throughout the Cretaceous, the Central Atlantic widened while the Tethyean region had a number of small plates and blocks that may have intermittantly impeded circulation through it. Even though the South Atlantic initially rifted at the time of the Parana mantle plume [~132 Ma], deep circulation was restricted by a number of barriers until much later. One such barrier, the Falkland Plateau, did not clear Africa until ~105 Ma leading to extensive salt deposits in the South Atlantic. Astrid Ridge, Maud Rise and the Mozambique Plateau probably formed an effective barrier to deep circulation between the Indian Ocean and the South Atlantic until after 100 Ma. One of the significant tectonic events during the Cretaceous was the opening of the Amerasian Basin of the Arctic Ocean. Opening is thought to have initiated during the Late Neocomian and was complete by the Aptian. It is conceivable that the Arctic Ocean as an isolated basin may have been responsible for the short term sealevel drop near the beginning of the Aptian on the recalibrated sealevel curve. Sudden flooding of other isolated basins, such as the South Atlantic and the Mesozoic Weddell Sea, may explain earlier Neocomian sealevel drops. An animation of the development of the Cretaceous oceans will be shown while opening of circulation gateways particularly into and out/of the South Atlantic will be highlighted.

Oceanic Anoxic Events and Plankton Evolution: Biotic Response to Tectonic Forcing during the Mid−Cretaceous

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Mid−Cretaceous (Barremian−Turonian) plankton preserved in deep−sea marl, organic−rich shale, and pelagic carbonate hold an important record of how the marine biosphere responded to short− and long−term changes in the ocean−climate system. Oceanic Anoxic Events (OAEs) were short−lived episodes of organic carbon burial that are distinguished by their widespread distribution as discrete beds of black shale and/or pronounced carbon isotopic excursions. OAE1a in the early Aptian (~120.5 Ma) and OAE2 at the Cenomanian/Turonian boundary (~93.5 Ma) were global in their distribution and associated with heightened marine productivity. OAE1b spans the Aptian/Albian boundary (~113−109 Ma) and represents a protracted interval of dysoxia with multiple discrete black shales across parts of Tethys (including Mexico), while OAE1d developed across eastern and western Tethys and in other locales during the latest Albian (~99.5 Ma). Mineralized plankton experienced accelerated rates of speciation and extinction at or near the major Cretaceous OAEs, and strontium isotopic evidence suggests a possible link to times of rapid oceanic plateau formation and/or increased rates of ridge crest volcanism. Elevated levels of trace metals in OAE1a and OAE2 strata suggest that marine productivity may have been facilitated by increased availability of dissolved iron. The association of plankton turnover and carbon isotopic excursions with each of the major OAEs, despite the variable geographic distribution of black shale accumulation, points to widespread changes in the ocean−climate system. Rates of seafloor spreading and hydrothermal activity increased in the late Aptian. Faster spreading rates drove a long−term (Albian−early Turonian) rise in sea level and $CO_2$−induced global warming. Changes in ocean circulation, water column stratification, and nutrient partitioning lead to a reorganization of plankton community structure and widespread carbonate (chalk) deposition during the Late Cretaceous. We conclude that there were important linkages between submarine volcanism, plankton evolution, and the cycling of carbon through the marine biosphere.

A Possible Record of Glacioeustatic Sea Level Changes from the Cenomanian−Turonian Western Interior Basin

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Cenomanian−Turonian (Upper Cretaceous) marine strata of the Western Interior Basin typically contain rich assemblages of foraminifera. Variations in the proportions of agglutinated, calcareous, and planktic taxa are used to characterize fluctuating water depths and/or to distinguish water mass influences, including cooler, less saline Boreal waters and warmer, more saline Tethyan affinities (e.g., Eicher and Worstell, 1970; Eicher and Diner, 1985; Fisher et al., 1994; Leckie et al., 1998; West et al., 1998). Agglutinated foraminifera and ostracods can be used to distinguish estuarine, lagoonal, and marsh facies (Tibert et al., in press). By analogy with modern foraminiferal distribution patterns, estuarine and lagoonal environments represent water depths 50%) in water depths deeper than 100 m on the continental shelf and slope. Wide ranging planktic to benthic (P:B) ratios and alternations of agglutinated to calcareous benthic populations can therefore be used to recognize and constrain ancient sea level amplitude.

The Cenomanian−Turonian Greenhorn marine cyclothem comprises a third−order eustatic sequence in the Cretaceous Western Interior Basin. Calcareous mudrock and marl accumulated across the western basin during much of the transgressive−regressive sequence. Within the Greenhorn Cyclothem, Leithold (1994) recognized six fourth−order carbonate cycles in prodeltaic deposits of Utah. Based on radiometric age dates of bentonites (Obradovich, 1993) and ammonite biostratigraphy, these six carbonate cycles are of variable duration (~150−950 kyr). We have subsequently traced these cycles across the U.S. Western Interior Basin including Black Mesa (northeastern Arizona), Mesa Verde (southwestern Colorado), Kaiparowits Plateau (south−central Utah), and Billings (south−central Montana). In addition, the fourth−order marine cycles deposited during the transgressive phase of the Greenhorn Cycle (Cycles 1−3) have been correlated into marginal marine facies of southwestern Utah where they are preserved as coal−bearing strata (Tibert et al., in press). Planktic foraminiferal maxima coincide with bulk carbonate maxima that record sea level high stands. We interpret the planktic:benthic fluctuations as sea level amplitude changes on the order of tens of meters.

The forcing mechanisms for these sea level changes are difficult to decipher. Correlation of the planktic and carbonate peaks across a large geographic area, coupled with the recognition of a forced regression in the lower middle Turonian (Cycle 5), suggest that allogenic processes controlled the observed stratal cyclicity. The amplitude and possible long eccentricity periodicity (400 kyr) of these cycles in the Milankovitch band (e.g., Meyers et al., 2001) suggest that glacioeustasy would seem a possible driving mechanism.

Nannofloral biogeographic patterns illustrate long−term climate change: warming/cooling trends in the Late Cretaceous Indian and Pacific Oceans

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Since the Late Triassic, when the nannoplankton began to produce calcareous platelets thereby causing a major shift in carbonate deposition from the shelves into the deep oceans, this diverse and abundant group of unicellular, planktonic marine algae have been intimately linked to global change. In modern oceans, it has been demonstrated that the distributions of certain sensitive nannoplankton taxa mirror 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 and their distributions.

Broad nannofossil palaeobiogeographic zones (PBZs) have been defined for the Late Cretaceous Indian and Pacific Oceans, at 5my intervals, based on a combination of semiquantitative and quantitative data from nine Indian Ocean and 16 Pacific Ocean DSDP/ODP sites. The taxa used in these definitions either displayed high relative abundances, or were not highly−abundant but did appear to be geographically restricted. Since modern nannoplankton distributions are determined by temperature and/or nutrient concentrations, so these latitudinally−distributed PBZs are interpreted as indicating discrete water−masses, possessing differing temperature and nutrient properties. Grossly, temperature is intrinsically linked with nutrient concentration, with warmer waters tending towards oligotrophy, whilst cooler waters are generally more eutrophic. Thus, movements of the fronts separating these PBZs through time can be used as proxies to primarily indicate warming or cooling trends. Data from the Indian Ocean shows a trend of Late Albian−Cenomanian cooling, Cenomanian−Turonian warming, and Turonian to Maastrichtian cooling, with possible warm phases in the mid−Campanian and Late Maastrichtian, and a Late Campanian−Early Maastrichtian cooling pulse. Data from the Pacific Ocean is currently being interpreted, and the results of this will also be presented.

Comparison of available oxygen isotope sea−surface temperatures (SSTs) with the PBZ−derived warming and cooling trends shows a good correlation between the two proxies, underlining the utility of nannofossils as proxies for Mesozoic climate change. However, it has been noted that correlation can be imprecise or offset because SST data is often generated without regard to a precise stratigraphic framework.

The Terrestrial Stable Isotopic Record of Aptian−Albian OAE1b in Palustrine Carbonates of the Cedar Mountain Formation, Utah: Implications for Continental Paleohydrology

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Nonmarine strata in the Cretaceous Cedar Mountain Fm (Barremian?−Albian) accumulated in the Western Interior foreland basin, preserving a record of semi−arid terrestrial paleoenvironments in the rain shadow of the Sevier mountains. We tested for coupling between marine, atmospheric, and terrestrial carbon reservoirs by analyzing the $\delta^{13}C$ chemostratigraphy of pedogenic carbonate glaebules in closely−spaced palustrine carbonate beds in two stratigraphic sections near Price Utah (150 m), and at Dinosaur National Monument (DNM; 60 m), looking for Aptian−Albian carbon isotope excursions. Both sections show organized structure that we have correlated to Aptian−Albian carbon isotopic segments C8 to C15 of Bralower et al. (1999, J. Foram. Res. 29:4:418−437), further supporting the use of palustrine carbonates for continental−marine correlations. The 5 per mil $\delta^{13}C$ shifts in our continental sections exceed those reported from coeval marine sections, as in the report of Jahren et al. (2001, Geology 29:2:159−162) on Aptian $\delta^{13}C$ changes in terrestrial C3 plants. A systematic offset of about 1.5 per mil between $\delta^{13}C$ values in the proximal foreland section at Price (heavier), and those at the more distal section at DNM (lighter) may be related to local $^{13}C$ enrichments in C3 floras that experienced greater moisture stress on the immediately leeward side of the Sevier mountains. Peak $\delta^{13}C$ values of −3 ‰ in the section at Price occur in segments C7−C8 and C12−C13 (OAE 1b), whereas minimum $\delta^{13}C$ values of −9.3 ‰ occur at DNM in segment C14. Peak $\delta^{18}O$ values of −3 VPDB occur in the Price section in segments C7−C8, with minimum $\delta^{18}O$ values of −9.5 ‰ occurring at DNM in segments C11−C12. Mean $\delta^{18}O$ values on the shoulders of the positive carbon isotope excursion coinciding with OAE 1b (segment C13) are the same at both sections (−8.5 ‰), but diverge in the C13 segment, with heavier values by about to 2 per mil in the more proximal section at Price, suggesting an intensification of aridity during OAE 1b. Individual carbonate beds are complex mixtures of micritic, microspar, and vein−filling sparry calcite components, with each showing unique diagenetic trends in C−O isotope space. Abundant microspars have trends conforming to meteoric calcite lines (MCLs), suggesting that they recrystallized in shallow meteoric phreatic groundwaters at surface MAT. Diagenetic analysis of a selected carbonate bed shows that micritic components produce a trend of covariant $^{13}C$ and $^{18}O$ enrichments of 1−2 per mil from the microspar MCL trend, suggesting pedogenic origin in a vadose environment. The MCL value in this bed (−7.5 ‰) yields a compatible groundwater $\delta^{18}O$ estimate with that from an independent paleoprecipitation proxy (sphaerosiderite horizon with MSL value of −4.0 ‰ from the Dakota Fm of Utah reported in White et al., 2001; Geology 29:363−366). Using a zonally−averaged Cretaceous MAT of 27° C for Utah, maximum $^{18}O$ enrichments in the micritic components suggest that up to 50 % of vadose fluid was lost to evaporation, exemplifying a method we are exploring for estimating evaporative fluxes from Cretaceous aridisols.

Warming in the subtropical Western Atlantic during Maastrichtian cooling: Hot tropics and latitudinal temperature gradients

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Temperatures at the tropical end of greenhouse latitudinal transects have posed as difficult a paleoclimatic puzzle as polar warmth. Simply stated, for greenhouse high latitudes to have been as warm as data suggest, the tropics should have been much warmer than most published estimates. Recent oxygen isotopic data from exquisitely preserved material at several tropical sites (e.g., Wilson and Opdyke, 1996; Pearson et al., 2001) may resolve much of the problem. These studies report low planktic $\delta^{18}O$ values suggesting hot greenhouse tropics and implying that early alteration of tropical planktic specimens in relatively cool bottom waters/pore waters was pervasive even in the well preserved samples used in most paleotropical studies. Further, evidence for hot tropics supports a proposition that temperature increased across all latitudes during warming intervals and decreased during cooling intervals. Results from the Maastrichtian at Blake Nose, though, show that the subtropical western Atlantic was warming at the same time high latitudes were cooling and demonstrate that controls on low latitude temperatures remain a problem for understanding greenhouse climates regardless of the absolute temperature in tropical/subtropical settings.

At three Blake Nose ODP/DSDP sites (390, 1050, and 1052) $\delta^{18}O$ values of various planktic foraminifera and fine fraction carbonate decrease by 0.5‰ to 1.5‰ from the early to the late Maastrichtian. Superimposed upon the long−term negative trend is a short−term negative shift that likely represents a brief pulse of globally recognized, late Maastrichtian warming. Burial depths at the Blake Nose sites range from < 150 m at 390 to > 450 m for the oldest samples from 1052. Preservation ranges from excellent to good with the poorest preservation occurring at the deepest levels of Site 1052. These most deeply buried samples have $\delta^{18}O$ values ~0.5‰ lower than values in correlative samples from the other two sites, and, consequently, the extent of apparent warming is least at 1052. We attribute the differences between 1052 and the other two sites to burial diagenesis. These burial effects, though, act in the opposite direction to the long−term decrease in $\delta^{18}O$ we observe. Similarly, diagenesis has not obscured the $\delta^{18}O$ record of the independently documented late Maastrichtian warming event. Thus, we are confident that the trend of decreasing planktic $\delta^{18}O$ values across the Maastrichtian at Blake Nose represents a paleoenvironmental signal. The size of the shift suggests ~4−6°C of warming or 3−4 ppt freshening of surface waters.

Apparent warming from the early to late Maastrichtian at Blake Nose is provocative because this 6 million year interval is generally considered to be a time of global cooling and, perhaps, includes high latitude glaciation. We can not rule out the possibility that Blake Nose data reflect a regional, western North Atlantic phenomenon rather than global, subtropical phenomenon, but our data suggest that poleward heat transport decreased during the Maastrichtian.

A quantitative evaluation and application of the results of a Maastrichtian (Late Cretaceous) coupled ocean−atmosphere model experiment using the HadCM3 AOGCM

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The Maastrichtian (Late Cretaceous) is a stage better known for its abrupt, enigmatic end, rather than for any inherent interest. Yet the K−T extinction event and its consequences, can only be understood in the context of the contemporary climate and environment. The Maastrichtian is a time of global cooling, but with no persuasive evidence of large−scale polar glaciation. Seaways, though beginning to close, continued to dominate the paleogeography of North America, Eurasia, South America and North Africa. The Arctic was almost fully land−locked, whilst in Asia highlands extended from Indonesia north through China and into NE Russia. The Maastrichtian is a stage with a large terrestrial and marine geological record on all continents and is present at a significant number of DSDP and ODP sites. Terrestrial fossil localities, with many recognizably modern forms, extend from the Antarctic Peninsular to Alaska and throughout the continental interiors of North America and Asia. As such the Maastrichtian provides an ideal time interval for which to model the climate and evaluate the results.

A series of atmosphere (AGCM) and coupled ocean−atmosphere (AOGCM) model experiments have been run using the latest Hadley Centre model, HadCM3. The details of this model, boundary conditions, the climate and ocean results are described in a separate presentation in this workshop (Valdes). Here is presented a quantitative and qualitative evaluation of the "veracity" of the experiments using a comprehensive dataset of geological climate proxies. These include fossil vertebrates, megafloras, paleosols, and stable isotope geochemistry. Preliminary assessment indicates that the AOGCM experiment better replicates "observations" than existing AGCM experiments.

While such data−model comparisons increase our understanding of model behaviour, the integration of data with carefully designed model experiments can be also used to address other geological problems. This is only possible because of the compilation of a comprehensive dataset of geological, tectonic and paleontological information, and the construction of a detailed, "hydrologically−correct," global paleo− topographic and −bathymetric digital elevation model (DEM). This DEM not only supplies an essential boundary condition for the modelling experiments, but also provides the context for investigating and further understanding processes on the surface of the Maastrichtian Earth, including the distribution and evolution of life.

Late Cretaceous, Western Interior Basin Cold−Seep Mounds (Tepee Buttes): Geographic, Stratigraphic, and Age Distribution in North America

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Late Cretaceous, Western Interior basin cold−seep mounds or tepee buttes, reported hydrocarbon emission (methane) sites, are anomalous carbonate bodies within basinal shales. Stratigraphic sleuthing has revealed the cold−seep mounds to be narrowly restricted in their geographic, stratigraphic, and age distributions. The geographic distribution ranges from the northern Black Hills southward to the Texas−Mexican border, restricted to roughly between 101°30" W and 105°30" W longitude. The age distribution of cold−seep formation consist of five discrete intervals during a time span of approximately 14 million years, basal Campanian through the Early Maastrichtian.

The oldest cold−seeps are reported from the upper Ojinaga Formation, West Texas, within basal Campanian Gulf Coast biozone, *Submortoniceras tequesquitense*. Later cold−seep mounds, the Tepee Buttes, are reported from the central interior of the basin (Black Hills to Colorado/New Mexico border) within the Pierre Shale. These occurrences are distributed within four intervals from the Middle Campanian through Early Maastrichtian within the Western Interior basin ammonite biozones of: 1) *Baculites perplexus* and *B. gregoryensis*, 2) *B. scotti* through *Didymoceras cheyennense*, 3) *B. reesidei* through *B. eliasi*, and 4) *B. grandis* and possibly *B. clinolobatus*. Comparisons in the geographic and temporal distribution of the interior cold−seep mounds to subsurface structures, basinal subsidence patterns, and strandline position, suggest an association between cold−seep formation and changes in basin tectonics, western strandline migration, and the possible delineation of the forebulge region.

Analysis of Sediment/Geochemical Accumulation Rates and Molluscan Evolutionary Rates during the Cenomanian−Turonian Biotic Crisis, Western Interior Seaway

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With ammonite/inoceramid species loss of up to 85% in the Western Interior basin, the Cenomanian−Turonian boundary event represents a significant biotic crisis. Hypotheses proposed for the driving mechanism of species turnover include mainly changes in benthic and water column oxygen levels associated with Oceanic Anoxic Event II, and changes in substrate consistency associated with limestone−marlstone alternation. Although the critical agent of biotic deterioration under oxygen deficient conditions is likely to be elevated pore water and bottom water sulfide concentrations, evidence for extensive and prolonged euxinia during OAE II in the Western Interior is lacking. In this study the main hypotheses for biotic turnover are reviewed in light of new sediment and geochemical accumulation rates, as well as recalculated evolutionary rates across the stage boundary. These new rates are based on a high resolution time scale developed through cyclostratigraphic analysis of the Cenomanian−Turonian Bridge Creek Limestone Member.

Evolutive harmonic analysis of an optical densitometry record from the central basin #1 Portland core (Colorado) permits detailed reconstruction of changes in sedimentation rate, including the quantification of hiatuses, thus allowing construction of an unbiased time−scale. The new high−resolution time scale facilitates an independent quantitative assessment of the rates of accumulation of environmentally sensitive geochemical proxies, and calculation of rates of evolutionary change (FA/kyr, LA/kyr) in the C−T boundary interval. We employ the new proxy flux data, and published paleobiologic, stratigraphic, and sedimentologic data, to assess secular paleoenvironmental change in the Western Interior sea (e.g., redox state of sediments/water column, productivity of pelagic autotrophs, changes in terrigenous silicilastic flux). Based on this, a series of major modal switches in sedimentation are identified. These modal switches may represent fundamental changes in the ocean−climate−sediment transport system, and include: (1) a shift from clay−dominated black shale (Hartland Shale Member) with evidence of sulfidic pore/bottom waters to carbonate dominated limestone−marlstone (lower Bridge Creek Limestone) lacking such evidence, (2) a shift to increased organic carbon/carbonate flux in the later portion of OAE II (lower Bridge Creek Limestone) that lacks evidence of extensive pore/bottom water sulfide, and (3) a shift to highest organic matter accumulation following OAE II (upper Bridge Creek Limestone) that shows evidence of sulfidic pore/bottom waters. Interestingly, the highest rates of extinction do not correspond to intervals with the greatest indication of sulfidic conditions. Further comparisons of paleoenvironmental data with molluscan evolutionary rate allow evaluation of alternate biotic controls, such as substrate consistency, turbidity, and nature/frequency of environmental disturbance.

High C/N and low del 15N values in black shales: Indicators of dysoxia−enhanced productivity?

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The organic matter contents of most black shales are marine in origin. Marine organic matter usually has atomic C/N values of 5 to 8 (Meyers, 1994, Chem. Geol. 144:289−302), yet C/N values in black shales curiously range between 20 and 40 (Rau et al., 1987, Earth Planet. Sci. Lett. 82:269−279; Meyers, 1989, Mar. Petrol. Geol. 6:182−189), which are values typical of land−plant organic matter. Del 15N values of Neogene and Quaternary marine sediments usually range between 4 and 8 per mil but are −2 to 3 per mil in Cretaceous black shales (Rau et al., loc cit), which again mimic land−plant compositions.

The excursions in the nitrogen−based organic matter source proxies provide clues to the conditions leading to deposition of black shales. Both elevated production and improved preservation of marine organic matter were important. Marine productivity is usually limited by availability of dissolved nitrate, but if a mid−water anoxic zone expands upward into the photic zone, then nitrogen−fixing cyanobacteria can flourish. These organisms produce organic matter having a del 15N value close to atmospheric nitrogen (0 per mil). The C/N values of most modern marine sediments are similar to algal organic matter (5−8), but high values (10−20) are common under areas of elevated marine productivity (Twichell et al., 2002, Org. Geochem. In press). Their explanation involves selectively improved preservation of organic matter during its sinking in which preferential degradation of amino compounds occurs under suboxic water−column conditions (Van Mooy et al., 2002, Geochim. Cosmochim. Acta 66:457−465). The anoxic mid−water conditions needed for nitrogen−fixation are an amplication of the conditions needed to increase modern C/N values and may have led to the higher C/N values found in black shales. The high C/N and low del 15N values imply that the marine nitrogen cycle changed to increase availability of nitrogen to marine production of organic matter during times of formation of black shales. By analogy to Mediterranean sapropels, the change may have been accompanied by increased availability of phosphorus from increased land runoff during periods of wetter climate.

Understanding Abrupt Climatic Disturbance in the Aptian−Albian

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A negative C isotope excursion of similar magnitude (−2 to −3‰) to that associated with the Paleocene−Eocene Thermal Maximum has recently been identified at the base of the Aptian Oceanic Anoxic Event (OAE) 1a (Jenkyns, 1995; Menegatti et al., 1998; Bralower et al., 1999), and documents a more complex relationship between $C_{org}$ burial and observed changes in the oceanic carbon reservoir than previously suggested. Moreover, this isotope anomaly is likely correlated to a negative excursion of even greater magnitude (~−5‰) that is delineated by the $\delta^{13}C$ values of terrestrial flora (Gröcke et al., 1999; Jahren et al., 2001). This apparent link may record concomitant changes in marine and terrestrial carbon cycling, perhaps brought on by greenhouse gas forcing. In an effort to better constrain the boundary conditions of the environmental perturbation associated with the Aptian−Albian OAEs, and to provide insight into potential forcing mechanisms, we have recently initiated a collaborative study of mid−Cretaceous deposits of the Sierra Madre Oriental of Mexico that integrates a series of stratigraphic, paleontologic, geochemical and isotopic proxies of carbon cycling, nutrient/productivity, and sea−level at a $10^5$ to $10^3$ year time scale.

To date we have documented the temporal and spatial evolution of the Barremian−Albian Cupido and Coahuila carbonate platforms of northeastern Mexico, and of the contemporaneous hemipelagic deposits that were laid down along the continental margin. Our chronostratigraphic framework places OAE1a in the "Cupidito" (shallow subtidal facies of the upper Cupido Fm.), and contemporaneous deep−shelf to hemipelagic facies of the Lower Tamaulipas Fm., and OAE1b in the upper Aptian to lower Albian ramp margin facies of the Aurora Fm. and coeval hemipelagic facies of the shaly La Peña Fm.. The sequence stratigraphic framework and relative sea−level curve for the Barremian−Albian platform carbonates of northeastern Mexico were defined using facies relationships, cycle stacking patterns, and the regional correlation of sequence−bounding unconformities integrated with biostratigraphic and chemostratigraphic (Sr and C isotopes) control (Lehmann et al., 1999; 2000). Correlation of our relative sea−level curve for the region with composite 'global' sequences and 'eustatic' curves indicates that three sequence boundaries record eustatic events. OAE1a occurred during the early phases of a long−term rise in sea level, whereas OAE1b is coincident with the peak of maximum flooding and demise of the Cupido platform. Our regional understanding of depositional relationships, sequence stratigraphy and sea−level history of the mid−Cretaceous in the Sierra Madre Oriental thus provides an ideal framework in which to evaluate the mode and temporal relationship between proxies of biological and chemical oceanographic change and records of sea level oscillation in OAE intervals.

Planktic foraminifer bioevents within Cenomanian−Turonian boundary interval at Pueblo, Colorado

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The time interval from late Cenomanian to early Turonian marks dynamic changes within marine environment recorded in shale and limestone sequences during deposition of the Bridge Creek Member of the Greenhorn Formation at Pueblo, Colorado. The main purpose of this work is to establish planktic foraminifer zonal scheme and datums and to correlate with already established molluscan biozonation.

Mid and Late Cretaceous SST and $CO_2$ from Exceptionally Well−Preserved Planktic Foraminifera

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Paleotemperature proxies such as the biogeography of plants and vertebrates as well as stable isotope records from marine carbonates demonstrate that the Cenomanian−Turonian interval records the warmest high latitude climates of the past ~200 million years. Curiously, most published tropical records of sea surface temperature (SST) are no warmer than today or are even cooler. Yet Late Cretaceous climate models that take into account the generally higher concentration of greenhouse gases and modern−like heat transport suggest that the tropics should be warmer and the high latitudes should be cooler than is indicated by most proxy temperature estimates. We have addressed this apparent paradox by analyzing exceptionally well−preserved foraminifera with glassy skeletons and primary shell textures. Our data sets now include analyses of four different sites spanning 30°N to 60°S. In all cases our data show oxygen isotope ratios that are more negative than analyses from chalk−hosted foraminifera at similar latitudes.

We used foraminifera preserved in claystone that have glassy shells similar to foraminifera caught in plankton tows. In some cases, the excellent foraminifer preservation is supported by the presence in the same strata of ammonites with aragonitic shells. Isotopic analysis of different species from closely sampled sequences has allowed us to recognize species with near−surface and thermocline habitats as well as to assess the variability in inferred temperatures. Species believed to be surface−dwellers based on their isotopic signature yield $\delta^{18}O$ of ~−3.5 to −4 ‰ in the Albian and early Cenomanian of ODP Sites 1050 and 1052; −3.9 to −4 ‰ in the late Cenomanian of DSDP 144, −4.2 to −4.5 ‰ in the late Turonian of DSDP 144, and −3.9 to −4.6 ‰ in the late Turonian of DSDP 511.

SST determinations depend upon a variety of assumptions about the isotopic composition of Cretaceous seawater. We must consider the effects of runoff−enriched slope water. The preservation of foraminifera in clay is consistent with significant runoff as is the tendency for many of the foraminifera to be unusually small. However, isotopic analysis of modern foraminifera across a depth transect (30 m to >1000 m) on the east Texas shelf and slope reveals no onshore−offshore trends in $\delta^{18}O$ despite large changes in average shell size and species diversity. Small errors in paleolatitude determination can also be magnified in tropical sites where the $\delta^{18}O$ for seawater can differ substantially inside and outside the Intertroipcal Convergence Zone. Recent estimates of paleo−pH have suggested that tropical temperatures may be underestimated by a few degrees owning to the high pH associated with high $pCO_2$ in the mid Cretaceous. Conversely, calculations of the amount of low temperature diagenesis in Cretaceous basalts suggest that Cretaceous seawater may have had less $^{18}O$ than today, causing paleotemperature estimates to be too high by about two degrees.

Conservative estimates of SST from our data, assuming an ice−free planet and the global mean $\delta^{18}O$ of seawater (−1 ‰), suggest temperatures ranging from ~28−30 ± 2°C. More realistic estimates based on allowance for variation in evaporation and precipitation with latitude suggest temperatures between ~30−33 ± 2°C. Tropical temperatures might have been even higher (up to ~36°C) if we allow for higher surface ocean pH associated with generally higher $pCO_2$ in the Cretaceous. The data also reinforce published evidence for a remarkably low thermal gradient between the Turonian tropics and the high southern latitudes of perhaps only 6°C, compared to the modern gradient of ~24−28°C. These SST estimates also imply that atmospheric $CO_2$ must have been very high (~6500−7500 ppm) during parts of the early Late Cretaceous to sustain both high tropical SST and warm southern latitudes.

Late Cretaceous Ocean: Coupled Simulations with the NCAR Climate System Model

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Deep ocean circulation may be a significant factor in determining climate. We describe two long, fully coupled atmosphere−ocean simulations with the NCAR Climate System Model (CSM) for the late Cretaceous (80 Ma). Our results suggest that higher levels of atmospheric $CO_2$ and the altered paleogeography of the late Cretaceous resulted in a surface ocean state − temperature, salinity, and circulation, significantly different than present. This, in turn, resulted in deep−water features, although formed by mechanisms similar to present, that were quite different from present. The simulations exhibit large overturning cells in both hemispheres extending from the surface to the ocean bottom and with intensity comparable to the present−day North Atlantic simulated overturning. In the Northern Hemisphere, the sinking takes place in the Pacific due to cooling of the much warmer and saltier waters compared to present−day. In the Southern Hemisphere, the sinking occurs primarily in the southern Atlantic and Indian Oceans. For a simulation with atmospheric $CO_2$ reduced from 6 times to 4 times pre−industrial concentrations, the southern branch is reduced by 35% due to less poleward transport of salty waters in the South Atlantic Ocean. Warm waters inferred from proxy data in deep−sea cores can be explained by the high−latitude sites of overturning. These results contradict the traditional hypothesis that warm Cretaceous ocean bottom waters must have formed by sinking in shallow low−latitude seas.

Foraminiferal Paleoceanography of the Cenomanian−Turonian Greenhorn Cycle of the Western Side of the U.S. Western Interior Sea

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Benthic and planktic foraminifera in the shales and mudrocks of the Cenomanian−Turonian Greenhorn Cycle are excellent proxies for sea level change in the Late Cretaceous Western Interior Seaway. By examining the foraminiferal assemblages, one can track the transgressive and regressive phases of the Greenhorn Cycle as well as gain detailed information on salinity, benthic oxygenation, productivity, and stratification of ancient water masses (Eicher and Worstell, 1970; Eicher and Diner, 1985; Leckie et al., 1991; West et al., 1998). In the Greenhorn Sea, oceanographic variables fluctuated through time due to seasonality, climatic cyclicity, and mixing of Boreal and Tethyan water masses. Percent carbonate is another useful proxy of water mass affinity and sea level change. This is because calcareous nannoplankton and planktic foraminifera thrived in the warm, normal marine Tethyan (southern) waters compared with the cooler, less saline waters of Boreal (northern) affinities. Leithold (1994) recognized six fourth−order depositional sequences within the third−order Greenhorn Cyclothem based in part on carbonate content. Foraminiferal assemblages can be used to define and correlate the fourth−order sea−level cycles superimposed on the Greenhorn Cycle.

In this study, foraminiferal assemblages and their response to sea level change were documented for two different sites: a drill core through the Tropic Shale in Escalante, Utah, and an outcrop section through the upper Belle Fourche Shale, Greenhorn Formation, and Carlisle Shale in Billings, Montana. Assemblage analyses are based on sample split counts of the >63 mm and >150 mm size fractions. Chronostratigraphy and correlation of the sections are based on molluscan biostratigraphy, percent carbonate, and widely dispersed bentonites. The first appearance of planktic foraminifera is diachronous from south (Escalante) to north (Billings). At both sites the planktic foraminifera appear suddenly and abundantly within the sections, accounting for 60−80% of the total assemblage. The proportions of planktics to benthics fluctuate during third−order transgression (fourth−order Cycles 1−3) but stabilize during highstand (Cycle 4). Planktic foraminiferal diversity is low throughout the Greenhorn Cycle (1−6 species, including biserial Heterohelix globulosa, and trochospiral Hedbergella delrioensis, H. planispira, and Whiteinella spp.). Planktic foraminifera became very rare along the western side of the seaway during third−order regression (Cycle 6).

In the >63 micron size fraction, the calcareous benthic, Neobulimina albertensis, dominates during Cycles 2, 3 and 4 at both sites, corresponding with peak transgression and highstand of the Greenhorn Sea. During peak transgression and highstand, the southern portion of the seaway was dominated by a warm, oxygen−poor Tethyan intermediate water mass. Fourth−order sea level change resulted in pulses of Gavelinella abundance due to shifting water masses, improved benthic oxygenation, and increased organic matter deposition. This yields a succession of Gavelinella followed by Neobulimina−dominated assemblages, due to this important interplay of food availability vs. oxygen level with changing sea level. Agglutinated benthics characterize the seaway during regression (middle Turonian), which reflects the displacement of Tethyan waters by cooler, less saline water masses from the North.

Patterns of planktic and benthic foraminifera in the Escalante (UT) core and the Billings (MT) section correlate broadly to Leithold's six carbonate cycles. The rapid and isochronous increase in CaCO3 at the Cenomanian/Turonian boundary at these two widely separated sites and the abrupt carbonate decrease in the basal middle Turonian (C. woollgari biozone, above bentonite TT5), suggest that water mass movement within the seaway responded to widespread changes in relative sea level.

Eustasy is the likely explanation based on the roughly 400 kyr cyclicity in the carbonate data (e.g., Meyers et al., 2001; Tibert et al., in press) and the observed forced regression represented by Cycle 5 (Leithold, 1994; West et al., 1998). Neobulimina tracks carbonate, and both are proxies for the warm, oxygen poor water mass(es) of Tethyan affinity. Tethyan waters persisted longer in the vicinity of the southern Escalante site.

Implications of an Atlantic gateway for the Cretaceous thermal maximum and atmospheric dynamics

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The Cretaceous thermal maximum was a major turning point in the history of Earth's climate. This interval of peak warmth in the Turonian has been attributed to very high atmospheric $pCO_2$ resulting from rapid outgassing rates, though crustal cycling rates are thought to have peaked in the Aptian−Albian interval. On the basis of coupled ocean−atmosphere model simulations of the mid−Cretaceous, we hypothesize that the deepening of the Atlantic gateway could have contributed to the Cretaceous thermal maximum. Differences between pre− and post−rifting climate experiments demonstrate substantial regional oceanographic changes in the North and South Atlantic basins that are consistent with oxygen isotopic evidence used to infer a Cretaceous thermal maximum. The model results help reconcile the paleoclimate record foraminiferal $\delta^{18}O$ with our understanding of climate dynamics.

In addition, these Cretaceous simulations demonstrate that a redistribution of heat in the tropics can have substantial global climate consequences. With the initiation of an Atlantic gateway, global average surface temperature increases by approximately 0.4°C due to an invigorated hydrological cycle and enhanced greenhouse effect. In this talk, the atmospheric dynamical consequences of the rifting of Africa and South America will be highlighted.

Carbon isotopic variation in woody, lacustrine, and marine organic matter as records of source and concentration of atmospheric CO2 through the Cretaceous

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Carbon isotopic research on Cretaceous organic matter has focused on three major facies: terrestrial woody, lacustrine algal/bacterial and marine algal. The least studied of the three being lacustrine systems. Detailed carbon−isotope stratigraphies have been published for marine organic in pelagic marine sections from many continental and oceanic localities. Deviating trends in isotopic values for carbonate compared to woody or marine organic matter at critical intervals in coeval sections can be interpreted in terms of elevated concentration of atmospheric CO2 with a volcanic source and an isotopic composition of about −7 per mil. Stratigraphic uncoupling of these isotopic records results from concentration−dependent photosynthetic fractionation for organic matter compared to concentration−independent precipitation fractionation for most carbonates. Deviating trends in isotopic values for woody compared to marine algal organic matter are expected under terrestrial climatic conditions that amplify the anatomical differences between leaves in high plant leaves and cells, filaments or blades in algae. Cretaceous lacustrine strata have been largely ignored from the perspective of carbon isotope stratigraphy and systematics. Research currently in progress on Cretaceous lakes and wetlands from the southwestern margin of the U.S. Western Interior seaway suggests wildfires and bacterial blooms as important factors in the carbon−isotopic stratigraphy for lacustrine facies.

The Early Cretaceous planktonic foraminiferal radiation: paleoceangraphic implications

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The first radiation of planktonic foraminifera was thought to begin close to the base of the Aptian. However, their recent study from some Lower Cretaceous successions revealed that this group started to diversify much earlier. Direct correlation with ammonites indicated that the first diversification occurred in the early Valanginian with the appearance of the first hedbergellids (H. sigali and H. aptica) followed in late Valanginian by the appearance of H. delrioensis−type and the first planispiral form. This small fauna in both species number and size seems to persist without apparent changes through most of the Hauterivian, the end of which is characterized by an abrupt short flourishing of the gorbachikellids. The lowermost Barremian coincided with a remarkable increase both in abundance and number of planktonic species and genera that continued through the Barremian accompanied by an overall increase in size. However, their stratigraphic distribution and abundance fluctuated rhythmically with increasing fluctuation intensity in late Barremian. This trend continued through the lower and lower upper Aptian with a further increase in number of species and overall abundance and size of specimens after the early Aptian Oceanic Anoxic Event 1a (OAE1a). This increase was accompanied by the progressive appearance of more ornamented morphotypes. By middle late Aptian, several species of the older hedbergellid and globigerinelloidid stocks progressively became extinct. The late to latest Aptian assemblages were mainly composed of large ornamented morphotypes that in turn become extinct around the Aptian/Albian boundary. Contrary to what written in recent years, no turnover in planktonic foraminifera coincided with OAE1a. Detailed study of the organic−rich Livello Selli (Italy) and equivalents revealed that the OAE1a planktonic assemblages are typically dominated by either clavate morphotypes or leupoldinids, cyclically alternating with faunas consisting of normal−sized, round−chambered morphotypes (the same species prior and after OAE1a). The early Valanginian planktonic diversification coincides with several events in other pelagic groups: hedbergellids first occurred as calpionellids drastically decreased in abundance shortly before their extinction; nannoconids decreased in abundance whereas coccolithophorids diversified, boreal dinoflagellates migrated to low latitudes, and diatoms became somewhat better preserved. These events protend changes in the water column derived from increased efficiency of the oceanic current system, which in turn derived from more contrasting seasonality (dry/humid) that increased the nutrient supply in surface waters creating more eutrophic conditions for hedbergellid diversification. This discrete seasonality continued through the Barremian−Aptian as supported by the rhythmic fluctuations in abundance and composition of planktonic assemblages induced by orbitally produced Milankovitch cycles. The dominance of more ornamented, large−sized morphotypes in late Aptian indicates the onset or strengthening of a weak thermocline by that time. The presence of a proto−thermocline was only temporary and was disrupted at the close of the Aptian (= extinction of all large taxa). The OAE1a represented only a temporary paleoenvironmental perturbation characterized in the upper water column by alternating low oxygen levels (proliferation of leupoldinids), to slightly richer oxygen levels (clavate morphotypes) or to better oxygenated waters (round−chambered taxa). The effects of the perturbation related to the OAE1a appear to have terminated only about one million years after the event as clavate taxa and leupoldinids persisted up to the G. ferreolensis Zone.

The Cretaceous marine osmium (Os) isotope record

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Relative to the Cenozoic, the marine Os isotope record of the Cretaceous Period is very poorly documented. The purpose of this abstract is two−fold First, to summarize the available data constraining seawater Os isotope variations during the Cretaceous. Second, to suggest how higher resolution records of Cretaceous seawater Os isotope variations might contribute to broader efforts to better understand the causative factors responsible for Cretaceous climatic extremes.

Os isotope analyses of Cretaceous marine sediments are few and far between, never the less it is unambiguous that this Period is characterized by large amplitude variations in seawater $^{187}Os/^{188}Os$. Data coverage is best during the latest Cretaceous where low resolution temporal resolution analyses from several pelagic clay sequences yield a coherent picture of seawater Os isotope variations. There is a pronounced minimum at the K−T boundary ($^{187}Os/^{188}Os$ as low as 0.168), preceded by higher $^{187}Os/^{188}Os$ ratios between 66 and 80 Ma, as high 0.7. Based on analyses of metalliferous sediments from Cyprus and Oman, there is an excursion to low $^{187}Os/^{188}Os$ ( = 0.5) close to the Cenomanian−Turonian bondary (CBT) from ratios as high as 0.68 in the early Cenomanian. By the late Coniacian $^{187}Os/^{188}Os$ recovered to 0.58. To our knowledge there are no data constraining the structure of the Cretaceous portion of the marine Os isotope record prior to the Cenomanian. Although the data described above are sparsely distributed in time, we suggest two potential applications of the Cretaceous portion of the marine Os isotope record. First we hypothesize that large amplitude seawater $^{187}Os/^{188}Os$ variations might be exploited in a manner similar to the marine Sr isotope record. In the latest Cretaceous the rapid decline in seawater $^{187}Os/^{188}Os$ from 0.7 to 0.4 over the last several million years of the Cretaceous may provide improved age estimates between magnetic reversal datums. Os isotope stratigraphy also may be a useful complement to Sr isotope stratigraphy within the Cretaceous quite zone.

There is a long standing hypothesis that "superplumes" played a causative role in mid−Cretaceous warmth, anoxia and enhanced carbon burial. The local $^{187}Os/^{188}Os$ minimum near the CTB (described above) is analogous to the well documented local minimum in seawater $^{87}Sr/^{86}Sr$ near the CTB, with both isotope records indicating relatively greater mantle influence on ocean chemistry. However, the dip in seawater $^{87}Sr/^{86}Sr$ spans a time interval that is too broad to investigate the relative timing of various phenomena in detail. In essence, the response time of the marine Sr isotope system is too slow to address these issues effectively. We hypothesize that the short marine residence time of Os will allow the marine $^{187}Os/^{188}Os$ record to provide a record of LIP emplacement history that is more highly resolved in time than that provided by the marine $^{87}Sr/^{86}Sr$ record. With this improved temporal resolution we believe it will be possible to place new constraints on the time scale and nature of LIP volcanism, and also to better correlate this record with data from the sediment record that constrain ocean anoxia and carbon burial rates.

Production and Preservation in the Cretaceous Western Interior Sea

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The burial of organic carbon in sediments constitutes a transfer of carbon from the oxidized atmospheric reservoir ($CO_2$) to the reduced lithospheric reservoir ($CH_2O$), and functions as an important control on atmospheric carbon dioxide and oxygen levels over geologic time. Increase in primary production of organic matter and decrease in its decomposition (preservation) have been hypothesized as the main mechanisms responsible for this transfer of carbon from atmosphere to lithosphere. However, the relative contribution of each process continues to be a source of debate. In the Cretaceous period, there are several well−studied intervals of organic−rich sedimentation (e.g., "oceanic anoxic events") during which basinal sediments likely became temporary sinks for atmospheric $CO_2$ with concomitant oceanic and climatic perturbations. Such events offer an ideal opportunity to study the controls on, and consequences of enhanced carbon burial. Although significant progress has been made through the use of many proxy methods, the lack of detailed time scales has made flux estimates difficult, thus placing an inherent limitation of the quantification of Cretaceous productivity and preservation.

In this study, Evolutive Harmonic Analysis has been applied to the rhythmically bedded deposits of the Cenomanian/Turonian Bridge Creek Limestone Member (Western Interior Basin) to develop a high−resolution orbital time scale during and following Oceanic Anoxic Event II. This time−scale allows calculation of accumulation rates for selected geochemical constituents that represent proxies for important processes in the depositional environment. The analysis identifies two distinct intervals of elevated organic carbon accumulation (during OAE II, and just following OAE II), and permits evaluation of the productivity and preservation hypotheses within them. The results indicate that the causes of organic matter burial are more complex than the classic end−member production and preservation models suggest. Based on these results we present a geochemical model that illustrates the controls on organic matter burial by assessing the linkage between organic carbon and molybdenum accumulation in sediments. The model explains our main findings that: 1) the first order control on organic carbon accumulation in Western Interior fine−grained deposits is the rate of export of organic matter to the sulfate reduction zone (SRZ), which is controlled by primary production and export, bulk sedimentation rate, and location of the SRZ in the sediment/water column; and 2) a threshold level of preservational conditions (combination of the last two factors in #1) dictates whether or not changes in production will impact organic carbon burial. In addition to the Bridge Creek data, a spatial data set from the Hartland Shale Member will be used to further illustrate the model.

How Consistently Do Regression Models of Foliar Physiognomy Predict Cretaceous Climates?

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The statistical relationship between leaf physiognomy and climate for modern plants is widely used by paleobotanists to reconstruct Late Cretaceous climate. Methods such as simple linear regression (SLR) and multiple regression (MR) are used to derive leaf/climate relationships for modern floras, which then are used to estimate temperature and precipitation from paleofloras. When applied to modern test sites, physiognomic methods provide good "ballpark estimates" of mean annual temperature (MAT) and mean annual precipitation (MAP) but can show significant discrepancies between estimated and measured climate. The magnitude of the discrepancy (up to 5°C for MAT) is determined by the choice of equation used to quantify the leaf/climate relationship, referred to here as the physiognomic transfer function.

To determine the extent to which estimates of Cretaceous climate are biased by the choice of physiognomic transfer function, we applied a variety of published physiognomic transfer functions to a well−preserved leaf megaflora from the latest Cretaceous (Maastrichtian) Jose Creek Member of the McRae Formation, southern New Mexico. The Jose Creek assemblage represents probable *in situ* leaf litter preserved in volcanic ash that was derived from vegetation growing in well−drained soil, providing sampling conditions close to those represented by many modern reference floras. The analyzed assemblage consists of 42 species of dicot leaves, which co−occur with 10 species of ferns, conifers, and thermophilic monocots. Calculations of MAT and MAP were made using raw physiognomic data and data adjusted to account for the over−representation of small leaves in modern leaf litter.

For the Jose Creek assemblage, calculated MAT is 16−25°C and calculated MAP is 600−1200 mm/yr, a range of over 8°C for MAT and 600 mm/year for MAP. For temperature, SLR models give less variable results than MR models. This is curious, because each SLR model of temperature is derived from a geographically distinct reference flora, while all MR models of temperature are derived from a reference flora that comprises different versions of the CLAMP (Climate Leaf Analysis Multivariate Package) database. For precipitation, each SLR and MR model provides somewhat variable results, depending on whether leaf size values are adjusted for taphonomic bias towards the preservation of small leaves. Variation in calculated temperature and precipitation, relative to the mean of all estimates, can exceed + 35%. However, the range of values is congruent with more qualitative estimates of climate derived from paleosols and plant life form, which indicate a warm subhumid subtropical climate for the Jose Creek Member. This implies that physiognomic transfer functions are probably accurate to the level of climate zone. However, further testing of physiognomic transfer functions is needed to determine their reliability and level of accuracy.

A new organic palaeothermometer for the mid−Cretaceous green−house world

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The mid−Cretaceous earth is often referred to as a "greenhouse" world, i.e. characterised by high atmospheric $CO_2$ levels (estimated to be 3−8 times pre−industrial $pCO_2$), general absence of polar ice caps, reduced temperature gradients from the Equator to the poles, and oceans much warmer than today. Although the green−house climate has received considerable attention as a possible analog for future climate change, there still exists a discrepancy between model−predicted tropical sea surface temperatures (SSTs) exceeding 32°C and considerably lower SSTs derived from del 18−O palaeothermometry on foraminifera. This inconsistency, the "cool tropical paradox," may be related to diagenetic overprinting and inaccuracies in the conversion of del 18−O values into SST. Furthermore, sea surface temperature records in the mid−Cretaceous are sparse and scattered due to the poor preservation of forams. We have recently developed a novel SST proxy based on the membrane lipids of marine crenarchaeota, nannoplankton which thrived in present and past oceans. A study of marine surface sediments from all over the globe showed that these organisms adjust the composition of their tetraether membranes lipids as a response to sea water temperature. This response can be well described by a linear relationship ($r^2 = 0.92$) and thus be used to determine SST from the tetraether membrane composition preserved in sediments. A study of late Quaternary sediments from the Arabian Sea confirms that the tetraether lipids contain a temperature signal. Importantly, a pilot study has indicated that mid−Cretaceous sediments up to the Albian contain these components and that their composition indicate much warmer temperatures for the tropics than present day temperatures (between 5−9°C) and del 18−O palaeothermometry, in line with global circulation model calculations.

The Cretaceous World: Plate Tectonics, Paleogeography, Paleobathymetry and Paleoclimate

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Eight global reconstructions are presented illustrating the plate tectonic, paleogeographic, paleobathymetric and paleoclimatic conditions during the Cretaceous. These maps are based on global compilations of sea floor spreading data, digital topography and bathymetry, and lithologic and paleofloral indicators of climate. The eight intervals represented include: early Maastrichtian, Campanian, Turonian/Coniacian, Albian/Cenomanian, early Albian, Barremian/Aptian, Hauterivian, and Berriasian.

These reconstructions (see Figure 1) are a visualization of 3D paleotopographic and paleobathymetric models composed of over 6 million pixel−points that capture digital elevation information at a 10 x 10 km geographic resolution and 40 meter vertical resolution. This quantitative, digital approach to paleogeographic modeling permits new ways to visualize and analyze the Earth's changing surface.

The process of building a 3D paleogeographic map begins with the digital topography and bathymetry compiled by NOAA (Smith Sandwell, 2001), the BEDMAP Project (British Antarctic Survey), and the IBCAO Arctic Project (Jakobsson et al., 2000). The topographic and bathymetric information is gridded at a 6−minute resolution, and the individual data points (pixel−points) are rotated back to their paleo−positions using the global plate tectonic model of the PALEOMAP Project. The resulting map is reconstruction of present−day bathymetry and topography in paleo−coordinates.

In the next processing steps, the digital elevation and bathymetric values are corrected to take into account the complex effects of thermal subsidence (Stein Stein, 1992), glacial rebound, tectonic and volcanic activity and erosion. The result is a revised, global paleotopographic and paleobathymetric surface. To complete the 3D paleogeographic model the new topographic surface is digitally "flooded" by raising or lowering sea level according to the estimates from eustatic sea level curves (e.g., Haq et al., 1987).

In the final step, the pixels are color coded by elevation and climate. The paleoclimatic assignments are made on the basis of paleofloras (Willis and McElwain, 2002) and a global database of lithologic indicators of climate (Boucot et al., 2002).

Hydrothermal Links Between Ocean Plateau Formation and Global Anoxia

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It has been recently recognized that the formation of Large Igneous Provinces (LIPs), in particular oceanic plateaus, correlates closely in time with a number of rapid, global oceanographic changes including the long recognized and well documented ocean−wide anoxic events of the mid to late−Cretaceous. Hydrothermalism associated with large−scale submarine volcanism (e.g. event plumes) may have been responsible for the periodic exhaustion of water column $O_2$, resulting in anoxic conditions and increased preservation of organic carbon. However, a causal relationship between these two, if it exists, is still unclear.

In order to determine a specific link between anoxic events and event plume hydrothermalism associated with ocean plateau eruptions, we are determining the distribution of major, minor and trace element abundances in pelagic carbonate and black shale sequences from a number of sites around the world. An important aspect of event plume hydrothermalism is that the chemical exchange of elements to seawater is controlled by volatility rather than solubility and therefore the abundance pattern of elements released to seawater are different than those derived from typical steady−state hydrothermal vents. Specifically, we are examining for evidence of event plume activity, in the form of appropriate trace metal anomalies, before, during and after the "Livello Bonarelli" Ocean Anoxic Event (OAE[2]). This prominent black shale layer has been correlated with the formation of the Caribbean ocean plateau (~ 90Ma). By looking at the stratigraphic position and global distribution of trace element anomalies from these three sites, we hope to further extend the knowledge about the distribution and timing of any biogeochemical responses (e.g. anoxia, isotopic changes) related to Caribbean Plateau eruptions and the associated hydrothermal activity.

Recently, we have measured ±30 trace, minor and major element abundances in whole rock samples by ICP−MS and ICP−AES analyses from three sites; Rock Creek Canyon section, Pueblo, CO, ODP Site 1138 from the central Kerguelen Plateau and, Bass River, NJ (ODP Leg174AX). After normalizing element concentrations to Zr to remove the effect of terrestrial sediment, prominent trace metal anomalies are obvious in both the Rock Creek Canyon and Kerguelen Plateau sections. Complete and detailed results from all three sites will be presented at this conference.

Foraminiferal Assemblages of the Upper Cretaceous Niobrara Cyclothem as Proxies for Sea Level Fluctuations in the Western Interior Sea, Mesa Verde, Colorado

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The late Turonian−early Campanian Niobrara Cycle of the Western Interior Seaway is the longest second−order cyclothem in the Upper Cretaceous. Despite this fact, it has received far less study than the preceding Cenomanian−Turonian Greenhorn cycle. Samples were collected in a 680 m section of Mancos Shale at Mesa Verde National Park, Colorado. The base of the Niobrara Cycle is represented by the Juana Lopez Member of the Mancos Shale in Colorado. The Cortez Member and overlying Point Lookout Sandstone define the end of the cyclothem.

Three, third−order transgressive cycles are recognized within the Niobrara cyclothem spanning a period of ~9 m.y. These cycles correlate with those defined by Molenaar (1983) across the Colorado Plateau, based on lithofacies and ammonite biozones. The cycles are recognized by increases in %CaCO3 and less clearly in % total organic carbon (TOC). They are designated Transgression 2 (T2), Transgression 3 (T3), and Transgression 4 (T4) after Molenaar (1983). T2 is represented by the upper Turonian Juana Lopez Member at the Mesa Verde site, T3 by the middle−upper Coniacian Smoky Hill Member, and T4 by the upper Santonian part of the Cortez Member. T2 is indicative of peak transgression within the cyclothem. Molenaar's appointed T1 transgression correlates to the lower Turonian Bridge Creek Member of the Greenhorn Cycle at Mesa Verde. At least two of the three transgressions of the Niobrara cyclothem are also recognized in events in the Upper Cretaceous of Utah. The correlations allow for a regional comparison to be drawn between different localities within the seaway. These cyclic episodes can be analyzed using foraminiferal, geochemical, and mineralogical data to develop a detailed paleoenvironmental record for the Niobrara cyclothem.

High planktic:benthic ratios (p:b) mark the transgressions of the Niobrara Cyclothem. These ratios reflect the advance of warm Tethyan water masses into the seaway. In addition, increased abundances of benthic infaunal taxa such as Neobulimina also coincide with the Coniacian Smoky Hill transgression. The marked increase in this benthic taxon suggests that it may be adapted to low oxygen conditions, like modern buliminids, and this is further supported by its association with the elevated levels of TOC, indicative of dysaerobic bottom waters likely due to the incursion of an Oxygen Minimum Zone (OMZ). Dysoxic to anoxic conditions in the seaway are also indicated by foraminiferal−free zones in the transgressive upper Santonian part of the Cortez Member. Low p:b ratios mark the regressive phases. Dysoxia in the seaway was caused by the incursion of an oxygen minimum zone with rising sea level, or by enhanced salinity stratification, particularly during regression.

# Extreme climates recorded in the Cretaceous High Arctic

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The Cretaceous of the Canadian High Arctic is represented by sedimentary and volcanic rocks of the Sverdrup Basin that are exceptionally well exposed on Axel Heiberg and Ellesmere Islands. These sequences contain evidence for short−term episodes of extreme warmth and cooling during the Late and Early Cretaceous, respectively.

## Extreme Polar Warmth

A Turonian to Coniacian (~92 to 86 Ma) vertebrate assemblage from a site with a paleolatitude of approximately 71$^{o}$ N implies that polar climates were warm (mean annual temperature exceeding 14$^{o}$ C) (*Tarduno et al., 1998*). This episode may correlate with evidence for extreme high−latitude warmth from oxygen isotope paleotemperature estimates from the Southern Ocean (*Huber, 1998*). The Arctic assemblage includes large (over 2.4 meters long) champsosaurs, which are extinct crocodile−like reptiles. The vertebrate fossils overlie subaerially erupted flood basalts of the Cretaceous Strand Fiord Formation. These lavas are part of a large magmatic pulse (or large igneous province), that may include large parts of Ellesmere Island and the Arctic Ocean basin. This magmatism, coupled with coeval volcanism at six other large igneous provinces, suggests that volcanic carbon dioxide emissions may have helped cause the peak in global warmth.

## Cool Polar Climate

In contrast to the extreme warmth of the Late Cretaceous, Arctic sedimentary rocks of mid− and Early Cretaceous age show evidence of cool conditions in the form of glendonite horizons. Glendonites (pseudomorphs after the hydrated calcium−carbonate mineral ikaite), are associated with glacial marine sediments of Permian to recent age. We are currently studying the biostratigraphy, magnetostratigraphy and geochemistry of Valanginian glendonite−bearing strata of the Canadian Arctic. Preliminary data suggest that the glendonite horizons represent relatively short ( less than 100−400 kyr) episodes at a time of low eustatic sealevel.

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Motion between hotspot groups in the Cretaceous

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Since the utilization of hotspots as a frame of reference (*Morgan, 1971*), the suggestion that some or all hotspots move with respect to each other has been proposed (e.g. *Molnar and Atwater, 1973*). The stakes in this long−standing debate are high. In one case, hotspots can serve as a reference useful for a wide range of studies, including those of past climate, which require knowledge of the paleoposition of continental and ocean plates. In another, some hotspot tracks primarily record motion of the underlying mantle, invalidating not only some plate reconstructions, but also measures of true polar wander (TPW), the theoretical motion of the entire Earth with respect to the spin axis (*Goldreich and Toomre, 1969*). The Pacific Ocean, with its striking examples of hotspot−related topography, offers many opportunities for tests of hotspot fixity. Basalt colatitude data from Ocean Drilling Program sites (Resolution and MIT Guyots) show little latitudinal motion for the mid−Cretaceous (130−95 Ma) Pacific plate. When compared to data from North America and the Atlantic, these Pacific data suggest relatively rapid (34 +/− 8 mm $yr^{-1}$) motion of the Atlantic hotspots relative to Pacific hotspots (*Tarduno and Gee, 1995*). The total offset amounts to a systematic reconstruction error of ~1300 km in the Atlantic realm. Late Cretaceous basalt colatitudes from the Hawaiian−Emperor chain (Detroit Seamount) suggest southward motion of the Hawaiian hotspots since 81 Ma (*Tarduno and Cottrell, 1997*), a result supported by recent investigations during Ocean Drilling Program Leg 197 (*Tarduno et al., in press*). Data from both time intervals indicate that cumulative offsets of the Earth relative to the spin axis during the past 130 million years have been less than $5^o$ (*Cottrell and Tarduno, 2000; Tarduno and Smirnov, 2001*). Instead, these new analyses of Pacific and other global data indicate large scale, episodic motion between groups of hotspots. The mid−Cretaceous motion is of special interest because it correlates with major volcanism on the Indian and Pacific plates, including formation of the Kerguelen and Ontong Java Plateaus (*Tarduno et al., 1991*), consistent with rapid mantle convection.

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Transfer of Carbon from Surface to Deep Ocean in a Greenhouse World

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The deep ocean appears hostile to life: dark, cold, and very little food. Food is mainly derived from primary productivity by phytoplankton in surface waters: many organisms consume it on its way down, so that oC, and metabolic rates of benthos would have been much higher. If oceanic productivity had been similar to today's, benthic faunas would have appeared oligotrophic at such high temperature. In fact, they appear to be have been more eutrophic as judged from the morphology of dominant taxa, even though faunal and geochemical data suggest that Greenhouse World productivity was lower than todays. In addition, deep−sea benthic foraminifera did not show significant extinction at Cretaceous/Tertiary boundary, when surface productivity collapsed.

Greenhouse−World faunas were non−analog to present faunas in morphology of taxa: common Recent deep−ocean species appeared at about the establishment of the Antarctic ice sheet (about 33.5 Ma), and have no morphological counterpart in older sediments. Species groups common in the Paleogene−Cretaceous declined after the establishment of ice sheets, to become extinct in the last few millions of years; they have no Recent morphological counterparts. These 'Greenhouse taxa' had apertural morphologies, thus probably feeding strategies, which have no modern counterpart. It thus seems as if Greenhouse World faunas are no true analogs of faunas in the present cold deep−oceans, where phytodetritus is deposited in little−altered, fresh form to the sea floor and used by opportunistic species. The lack of evidence for strong bentho−pelagic coupling in warm oceans might be explained by the existence of different processes of carbon transfer from surface to deep oceans than in cold oceans, or by a greater importance of primary productivity of food on the ocean floor itself, by chemosynthetic bacteria. We do not know which (if any, or both) of these possible answers is right, but Recent and future ODP drilling (e.g., Shatsky Rise, Paleogene transect, Walvis Ridge, Demerara Rise) can be expected to increase our understanding of the non−analog worlds of the past and gain improved insight in the transfer of organic carbon from the surface to the deep ocean, a process of major importance for understanding the fate of atmospheric $CO_2$.

The Late Valanginian Event: Productivity and Ecological Changes

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Quantitative analyses of calcareous nannofloras and geochemical investigations were carried out on the Berrisian−Hauterivian Polaveno roadcut (Northern Italy), a very expanded and continuous section with a good bio− magneto− and chemostratigraphic control.

Nannofossils were quantified in smear slides and thin sections. On each smear slide at least 300 specimens were counted, whereas all the specimens present in 1 $mm^2$ were counted in each thin section. Fluctuations in nannofossil total abundance, diversity and abundance of single taxa reflect paleoenviromnental changes in the surface waters. The most marked fluctuations in both absolute and relative abundance concern the group of calcareous nannoplankton named nannoconids. This group experienced a sharp decline across the carbon isotope positive excursion, globally documented.

The nannofossil assemblages of the Late Valanginian were dominated by W. barnesae, with relative increase of Diazomatolithus spp., probably indicating higher fertility conditions as further supported by the decline in the oligotrophic nannoconids. An ascent in Sr/Ca ratios in these nannofossil carbonates in the Late Valanginian supports this interpretation of enhanced productivity. This increase slightly leads the carbon isotope excursion, and is coeval with the onset of the nannoconid decline. The tight correlation between increase in Sr/Ca ratios in the Polaveno section and in Atlantic sediments further suggests that this productivity event was global.

The nannoconid decline and productivity increase probably were induced by changes in nutrient content caused by the Early Cretaceous volcanic activity connected with the implacement of the Paranà Plateau and the "pulse" in the seafloor production.

These volcanic and tectonic events provoked excessive $CO_2$ levels in the atmosphere favouring warm and humid conditions that induced an accelerated transfer of nutrients from the continents to the oceans increasing the fertility of surface waters. Also, a nutrification event might have been directly caused by hydrothermal processes connected with the igneous activity.

Sediment origin and trace element enrichments in black shales during the Cenomanian−Turonian Boundary Event in the Gubbio Core, central Italy

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The mid− to Late Cretaceous "greenhouse" world was characterised by elevated temperatures and atmospheric $CO_2$, ice−free poles, equable climates, and generally sluggish circulation. The Cretaceous stratigraphic record is punctuated within several important organic−rich shale intervals representing quasi−global "Oceanic Anoxic Events" (OAEs). One of the most spectacular expressions of these OAEs is the Livello Bonarelli of central Italy, deposited during the Cenomanian−Turonian boundary (OAE2) at around 93.5 Ma. In the Umbrian−Marche Basin in Italy, the Livello Bonarelli consists of approximately 1 m of pyrite−rich black shales interspersed with radiolarian sandstone layers, and contrasts sharply with the extensive over− and underlying siliceous limestones. The duration of OAE2 deposition is assumed to be between 100 and 500 kyrs.

For this study, 42 Livello Bonarelli samples (average interval ~2 cm) were taken from the Gubbio Core, drilled from the Contessa Quarry. Powdered samples were analysed for $C_{tot}$, $C_{org}$, $S_{tot}$, and several major− and minor elements using X−ray fluorescence (XRF) on fused borate disks. These sediments, characterised by high $C_{org}$ (up to 23%), S, and $SiO_2$ contents (up to 95%) consist of a simple two component mixing system ("average shale"−$SiO_2$). Major element concentrations are low, except for Si and P, owing to a dilution effect by high levels of excess silica (52% on average). As Al−normalised ratios for heavy elements such as Rb, Zr, taken as proxies for higher energy environments, are close to "average shale" values, it is postulated that the excess $SiO_2$ represents biogenic opal rather than quartz.

Most elements, when compared to associated $Al_2O_3$ data, plot along "average shale" lines. Elements such as Ti, Mg, K, Rb, Zr, show positive relationships with $Al_2O_3$, pointing to homogeneous source area material. Most minor elements (As, Co, Cr, Cu, Mo, Ni, Pb, Sr, U, V, Y, Zn), many of them redox−sensitive or sulphide−residing, are strongly enriched in the black shales, based on Al−normalised ratios, documenting the absence of oxygen and potential availability of hydrogen sulfide in the water column, while high Zn concentrations hint at elevated underwater volcanism during this time interval. Lower than "average shale" MnO concentrations (0.01% compared to 0.11%, with corresponding Mn/Al ratios of 34.5 and 96.4 respectively), are indicative of suboxic bottom waters conditions through which more soluble $Mn^{2+}$ (reduced in the sediments) is exported via an oxygen minimum zone in an open marine environment during or shortly after deposition. Ba is also present in very high concentrations (up to >3%, with a weighed average of 0.98% for the entire Livello Bonarelli), and is possibly indicative of high paleoproductivity in this area. This is supported by the high P concentrations, which hint at nutrient availability at this site.

Latest Cretaceous Global Vegetation: Current Understanding and Areas for Future Study

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Four major approaches have been used to reconstruct latest Cretaceous vegetation. Biome reconstructions have mapped the distribution of climatically sensitive sediment types, palynomorphs, and plant megafossils, and diagnosed individual biomes using suites of environmental features and patterns of taxonomic co−occurrence. Physiognomic analyses of plant megafossils have used the adaptive characteristics of leaf assemblages and the distribution of life forms to reconstruct vegetation and the climatic parameters under which it grew. Climate modeling studies have used the output of Atmospheric General Circulation Models (or AGCMs) to predict global vegetation and fill in the gaps between data points, using the correlation between modern climatic parameters and the distribution of vegetation. Biogeochemical models have used the output of AGCMs to run process−based models of net primary productivity, leaf area index, and soil carbon.

All four approaches have significant areas of agreement. One area of agreement is the widespread distribution of forest vegetation at high latitudes, which indicates warmer summer and winter temperatures than at present. A second area of agreement is the poleward expansion of cold−sensitive plants and fungi. A third area of agreement is a major (1.5 to 2x) increase in net primary productivity and vegetation carbon relative to the Recent, with a significant fraction of vegetation carbon located at high latitudes. Additional areas of agreement include the occurrence of high soil carbon (i.e., coals) at polar latitudes in the Northern Hemisphere, and large areas of desert and semi−desert vegetation at subtropical latitudes in South America, Africa, and Asia.

All four approaches also have significant areas of disagreement. In equatorial regions, coal distribution and climate model output suggest areally restricted tropical rainforest and areally expanded tropical semi−deciduous forest, while biogeochemical models and patterns of provincialism in palynomorphs suggest a relatively broad equatorial band of dense tropical evergreen forest. At middle latitudes, plant megafossils and palynomorphs indicate a significantly greater poleward expansion of cold−sensitive plants than that predicted by climate models. At a global scale, published estimates of total vegetation carbon based on the biome approach are lower than those based on biogeochemical modeling. Resolution of these and other discrepancies requires expanding the global database of plant megafossils and palynomorphs, especially through the analysis of new floras from poorly understood regions such as the tropics; conducting additional simulations of climate and vegetation using coupled Earth−system models; evaluating uncertainties in paleobotanical data and model output; and better understanding the response of vegetation to Cretaceous levels of atmospheric $pCO_2$.

Coupled Ocean−Atmosphere−Vegetation Models of Warm Climates

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Computer climate models provide a useful tool for examining the processes influencing Cretaceous climates, and a large scale (global) perspective to aid in the interpretation of the proxy climate indicators. In turn, the geological data represents an extreme test of the climate models. Previous work in computer modelling of warm climates such as the Cretaceous and Eocene has often been limited to simulating part of the total climate system. Most commonly, simulations have been performed with atmospheric models coupled to either prescribed sea surface temperatures or a simple ocean model. Alternatively, ocean models have used simple parameterisations of the atmosphere.

In this paper we will review past work and present new simulations using some of the very latest coupled ocean−atmosphere−vegetation models. Our main focus will be on the late Cretaceous (Maastrictian) but work on the mid−Cretaceous and early Eocene will also be mentioned. We are using a version of the Hadley Centre climate model. The coupled model is predicting very warm tropical ocean temperatures, and relatively warm benthic temperatures. Deep water formation is mainly at high latitudes, and is seasonally varying, with the deepest mixing occurring off the coast of Antarctica. Vegetation feedback can be important locally but has only little impact on the global mean. The reasons for the warmth will be discussed and the results will be compared to data. Winter temperatures in continental interiors continue to be the major problem for model−data comparisons. The extent of the disagreement will be considered.

Evidence for rapid climate cooling during positive d13C excursions within the Middle and Late Cenomanian derived from oxygen isotope data of brachiopods and belemnites

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The Cenomanian time interval is considered to be the warmest period in the mid−Cretaceous greenhouse earth, and is additionally characterised by two positive $\delta^{13}C$−excursions within the Middle Cenomanian A. rhotomagense and the Upper Cenomanian M. geslineanum Zones. Both $\delta^{13}C$−excursions reflect perturbations of the global carbon cycle, and are associated with brief occurrences of the boreal belemnite Praeactinocamax as transgressive pulse fauna within the North European Province. New $\delta^{18}O$−data of well−preserved terebratulid and rhynchonellid brachiopods and belemnites from sections in southern England (Southerham, Eastbourne) exhibit the first high−resolution palaeotemperature record covering the Early Cenomanian to Early Turonian time. The long−term record of brachiopod−$\delta^{18}O$ values shows a continuous trend of climate warming from 14.4 °C in the Middle Cenomanian to 20.3 °C in the Lower Turonian. Superimposed on this long−term trend, periods of very rapid cooling occurred in relation to the Middle and Late Cenomanian $\delta^{13}C$−Events. The Middle Cenomanian $\delta^{13}C$−increase is predated by a rapid $\delta^{18}O$ increase (−1.5 to −0.2 ‰) corresponding to a sea−level fall within the C. inerme Subzone. Maximum $\delta^{18}O$ values (0.5 ‰) are reached with the onset of transgression in the basal T. costatus Subzone and the occurrence of P. primus. A similar pattern is visible during the Upper Cenomanian $\delta^{13}C$−excursion. $\delta^{18}O$ values of brachiopods and belemnites indicate rapid cooling during a sea−level fall followed by subsequent warming after transgression and the short−termed occurrence of P. plenus. Within both Cenomanian events, the decrease of sea−floor temperatures has a similar magnitude, and are about 8 °C if no changes in $\delta^{18}O$ of seawater are considered. The linkage of rapid $\delta^{18}O$ increases with sea−level falls and with the south−spread of boreal taxa suggests that climate cooling could have been coupled to the build−up of ice−sheets and changes in ocean circulation, and could have initiated perturbations within the global carbon cycle.

Coniacian−Santonian (OAE3) black shale formation and African climate variability: a reference section from the eastern tropical Atlantic at orbital time scales (ODP Site 959, off Ivory Coast/Ghana)

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The Coniacian/Santonian anoxic event (OAE3) is the final of the Cretaceous OAEs and documents one important step in the transition from the Cretaceous greenhouse− to the Cenozoic icehouse−world. Compared to extensive research on the early and mid−Cretaceous OAEs, little is known about the evolution and the climate impact of the final, Coniacian/Santonian OAE3. We present detailed terrigenous and marine proxy records from ODP Site 959 (eastern tropical Atlantic off Ivory Coast/Ghana), which allow to assess controls on tropical African climate, continental run−off, and the associated formation of oil−prone, marine black shales.

At ODP Site 959, Coniacian to lowermost Campanian sediments (CC13 to CC16) are composed of alternations of finely laminated and homogenous black shale units, which we use to reconstruct the mechanisms and feed−backs of orbital forcing, land−sea interaction, and phasing of terrigenous and marine records. Orbital tuned, high resolution (down to about 300 years) organic and inorganic geochemical records from biozone CC15b (late Coniacian to early Santonian) evidence cyclic changes in depositional boundary conditions, which occur at the main frequencies of the Milankovitch bands (see Hofmann et al. for further information). Two opposing depositional modes are supported, defining boundary conditions for marine black shale accumulation and background sedimentation in relation to African climate dynamics. The transition between both modes occurred rapidly on millennial and shorter time−scales. The data propose that the latitudinal displacement of African climate belts in conjunction with fluctuations in ocean circulation were key mechanisms that forced marine organic carbon accumulation.

During the black shale mode, wind−driven upwelling in the area of ODP Site 959 was fostered leading to the enhanced accumulation of marine kerogen type I organic matter (TOC up to 16%). Preservation of specific biomarkers indicative for photic zone anoxia, i.e. isorenieratane derivates, support at least temporarely extreme (sulfidic) conditions in the upper water column, somehow comparable to the Cenomanian−Turonian OAE2. Simultanously, low Si/Al and K/Al ratios indicate enhanced continental precipitation and excess mineral run−off (e.g. Aluminium) from extensive African lateritic soil deposits to the early Ivorian Basin. In contrast, the background mode documents periods of low accumulation and preservation of kerogen type II/III organic matter. High Si/Al and K/Al ratios in these sediments support a pronounced eolian signature from southern, more arid African source areas. Apart from these differences in atmospheric and oceanic circulation, general conditions for marine organic carbon accumulation remained favorable along the southern slope of the Ivorian Basin as indicated by continously elevated TOC concentrations of about 3% (see Beckmann et al. for further information).

Global climate modelling corroborates the two endmember modes of deposition off Equatorial Africa. Accordingly, precessional forced fluctuations in precipitation and air temperature probably have triggered short−term changes in aridity and humidity over central and western Africa.

Climatic forcing of nannoplankton evolution during Oceanic Anoxic Event 1−d

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Changes in the nature of oceanic surface water masses during oceanic anoxic events (OAE) were significant drivers of phytoplankton evolution. As an example, well−preserved nannofossil assemblages in upper Albian and lower Cenomanian hemipelagic sections from Ocean Drilling Program (ODP) Leg 171b record the early history of the establishment and adaptive radiation of the genus Eiffellithus. Seven distinct taxa (herein grouped as "early eiffellithids," "small eiffellithids" and "large eiffellithids") evolved during the relatively short interval from 101.5 to 100.0 Ma. Newly evolved species tended to remain at low abundance levels until a significant disruption in the pelagic realm resulted in the precipitous decline of the dominant species. This decline provided open niche space in the pelagic realm into which the new species could rapidly rise to dominance. These major disruptions correspond to significant changes or shifts in the sedimentological and carbon isotopic records associated with the late Albian Oceanic Anoxic Event (OAE−1d), suggesting that major changes in the strength of deep mixing and the structure of the surface water mass drove the early adaptive radiation of this genus. The two oldest taxa ("early eiffellithids") dominated the first 700 K.y. of eiffellithid history, but were suddenly replaced by the "small eiffellithids" and "large eiffellithids" coincident with the first occurrence of black shale (signaling the onset of OAE−1d) and its attendant negative carbon isotope shift. "Small eiffellithids" dominated the assemblages associated with OAE−1d, while "large eiffellithids" remain a stable, secondary component. The final black shale interval (approximately coincident with a positive carbon isotope excursion) corresponded with the rapid decline and subsequent extinction of one of the "small eiffellithids." This horizon marked the end of the peak in the conditions that resulted in significant organic carbon storage, although the sediment continued to be deposited under dysoxic conditions until the end of the Albian, as is illustrated in the elevated total organic carbon (TOC) levels in the uppermost Albian from ODP Hole 1050C. The end of deposition of organic−rich facies at the Albian/Cenomanian boundary brought the ultimate decline and extinction of the "small eiffellithids" and the rise to dominance of the "large eiffellithids," especially the large morphotype of Eiffellithus turriseiffelii. The close correspondence of species originations, changes in dominance, and species extinctions to changes in sediment TOC and significant carbon isotope shifts indicates that the variability in the surface water mass during OAE−1d was the principle environmental forcing mechanism behind the adaptive radiation of this genus during the late Albian.

Oxygen isotopic reconstructions of middle Cretaceous precipitation: model−data comparisons for North America

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The oxygen isotopic composition of siderite spherules from middle Cretaceous wetland paleosols have been used to reconstruct paleolatitudinal precipitation gradients for the greenhouse setting of mid−latitude North America. These published results (White et al., 2001, Geology, v. 29, no. 4, p. 363−366) indicate that the oxygen isotopic composition of precipitation was ~4 per mil depleted relative to comparable modern low−elevation coastal settings free of monsoons. More specifically, along the mid−latitude eastern margin of the North American Western Interior Seaway, middle Cretaceous precipitation rates are interpreted to have ranged from ~2500 to ~4100 mm/yr.

Here we present our new data from coeval east coastal plain deposits of North America, and published values from the North Slope, Alaska, to complement the Western Interior data set. These new data indicate that our earlier assessment of the Western Interior, extended north using the published North Slope data, are accurate. That is an enhanced greenhouse hydrologic cycle, and the presence of the Western Interior Seaway, led to much higher precipitation rates than those observed in comparable settings today.

Some of the east coast data (Nova Scotia, New Jersey, Delaware) are compatible with a latitudinal gradient in precipitation model. However, in Alabama samples, and some of the New Jersey and Delaware samples, calculated oxygen isotopic values for middle Cretaceous precipitation can be substantially more depleted (by up to 3 per mil) than the values observed at comparable latitudes in the Western Interior. An argument can be made for a "reversed" latitudinal gradient along the middle Cretaceous east coast, from that observed in Western Interior strata.

We explore these relationships using a stable isotope version of the GENESIS atmospheric general circulation model. The modeling effort uses relative sea−level highstand and lowstand settings, and 4X present−day atmospheric carbon dioxide contents. We first specify sea surface oxygen isotopic compositions as uniformly −1.2 per mil across the middle Cretaceous oceans. Second, we impose a sea−surface oxygen isotopic profile based on literature compilations and GENESIS−derived sea−surface temperatures. Our initial results indicate that the Western Interior data sets mostly match the model simulations. Model runs are ongoing.

Integrated terrestrial and marine climate history of the terminal Cretaceous

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Terrestrial climates near the time of the end−Cretaceous mass extinctions are poorly understood. We estimate and correlate paleotemperatures for the terminal Cretaceous (~66.7 to 65.5 Ma), using megafloral data from North Dakota and foraminiferal data from four middle− and high−latitude sites. Both plants and foraminifera indicate warming near 66.0 Ma, a warming peak from ~65.8 to 65.6 Ma, and cooling near 65.6 Ma to pre−warming temperatures, which lasted into the early Paleocene. At similar temperatures, Cretaceous floras from North Dakota were rich, but Paleocene floras were impoverished. Climatic and facies changes are insufficient explanations for plant extinctions in this area, which we attribute to the effects of bolide impact.

Testing the greenhouse hypothesis and latest Albian oceanic anoxic event

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The mid−Cretaceous (~120 to 80 Ma) witnessed some of the warmest polar temperatures yet experienced by multi−cellular life on Earth, repeated reef drowning in the tropics and a series of "oceanic anoxic events" (OAEs) that promoted widespread deposition of organic carbon (C−org)−rich marine sediments and biotic turnover. The underlying cause of mid−Cretaceous warmth is widely attributed to tectonically driven increases in atmospheric levels of greenhouse gases (e.g. carbon dioxide) while a wide range of competing hypotheses seek to explain the climatic causes and effects of OAEs.

Here, I present new stable isotope records from individual species of remarkably well−preserved clay−hosted planktonic and benthic foraminifera in western tropical Atlantic sites (ODP 1052, Blake Nose and DSDP 144, Demerara Rise). Stable isotope records from benthic foraminifera from ODP Site 1052 provide new constraints on the problem of the underlying cause of oceanic anoxia during the latest Albian. Planktonic foraminifera of Turonian age from DSDP Site 144 yield the warmest equivalent oxygen isotope sea−surface temperatures (SSTs) yet reported for the entire Cretaceous−Cenozoic. These data (i) lend support to the hypothesis of a "Cretaceous greenhouse" and (ii) strengthen the case for a Turonian age for the Cretaceous thermal maximum (KTM). At the same time however, these data highlight a 20−40 m.y. mismatch between peak Cretaceous−Cenozoic global warmth and peak inferred tectonic $CO_2$ production.

This mismatch is either an artifact of a "hidden" Turonian pulse in global ocean−crust cycling or real evidence of the influence of some other factor on atmospheric $CO_2$ and/or SSTs. A hidden pulse in crust cycling would explain the timing of peak Cretaceous−Cenozoic sea level (also Turonian) but other factors are needed to explain high−frequency (~10−100 ka) instability in middle Cretaceous SSTs reported previously (Wilson and Norris, 2001, Nature 412, p. 425−429).

Cenomanian−Turonian Oceanic Anoxic Event (OAE2) at 53° South Latitude: A Progress Report

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A 1−m thick, lowermost Turonian black claystone marks the OAE2 in ODP Core 1138−69R on the Kerguelen Plateau (53° 33'S, 75° 58'E). Deposited on a subsiding volcanic edifice, it overlies a lower Turonian, neritic sandy packstone replete with serpulid worm tubes, beneath which lie glauconitic marine sandstones (with pecten shell fragments) and fluvial pebble conglomerates above igneous basement (with subaerial volcaniclastic rocks and basalt flows). The pectens provided a strontium−isotope date interpreted as earliest Turonian, whereas the fluvial deposits contain upper Albian to lower Cenomanian palynomorphs. The strontium−isotope date agrees with those from planktonic foraminifers (Whiteinella archaeocretacea Zone) and calcareous nannofossils (equivalent to CC10b or UC6a).

The black claystone bed, essentially devoid of calcareous nannofossils, gives way upsection to laminae and then beds containing progressively more nannofossils and other calcareous microfossils as might be expected during the ventilation of an anoxic depositional environment. Such an environment could have existed in the nearshore shelf region of the then emergent Central Kerguelen Plateau during the major transgression postulated as a contributing cause of the OAE2. The progressive subsidence of the volcanic platform could explain in part the lithologic succession from nearshore, oxidized sediments below to the meter−thick black claystone bed above.

The core also contains a rich palynomorph flora of spores plus plant materials from ferns, including axes, leaves with sporangia, and a young enrolled frond. These undoubtedly contribute to the $\delta^{13}C$ bulk isotopic values that range only as low as −25.82 per mil within the m−thick claystone bed. Total organic carbon ranges as high as 20.42. Upsection, as TOC decreases, bulk carbon values become more characteristic of open marine pelagic carbonates.

Among the calcareous nannofossils, the eprolithids display an evolutionary succession ranging progressively from E. floralis (9−rays) to E. octopelatus (8 rays), E. eptapetalus (7−rays) to the closely related, short−rayed Lithastrinas moratus (7 rays, straight). Eprolithus rarus (6 rays) was noted higher in the section (Core 67), where it was accompanied the the long−rayed Lithastrinus septenarius (7−rays, curved). The presence at this relatively high latitude of this extensive lineage of age−diaognistic taxa, originally described at lower latitudes, is attributed to the exceptionally warm climates that characterized the early Turonian world−wide.