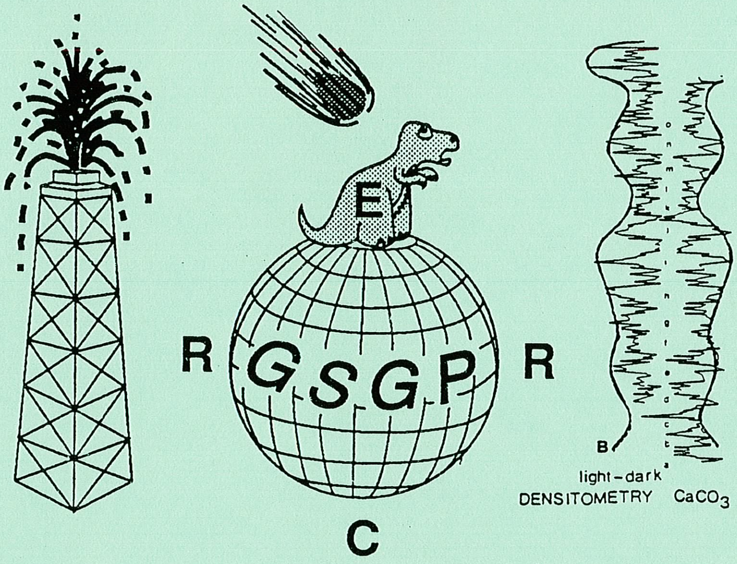
SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS

## RESEARCH CONFERENCE

# CRETACEOUS RESOURCES, EVENTS, AND RHYTHMS



JOI-USSAC

DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

# PROGRAM AND ABSTRACTS

SOCIETY OF ECONOMIC PALEONTOLOGISTS AND MINERALOGISTS (SEPM)

RESEARCH CONFERENCE

ON:

# *CRETACEOUS RESOURCES, EVENTS, AND RHYTHMS*

AUGUST 20-24, 1990
DENVER, COLORADO

CO-SPONSORED BY THE GLOBAL SEDIMENTARY GEOLOGY PROGRAM (GSGP) WITH SUPPORT FROM THE JOINT OCEANOGRAPHIC INSTITUTIONS — U.S. SCIENCE SUPPORT PROGRAM (JOI-USSSP) AND THE U.S. GEOLOGICAL SURVEY

## SEPM-CRER RESEARCH CONFERENCE ORGANIZATIONAL COMMITTEE

### RESEARCH CONFERENCE COMMITTEE:

- Michael Arthur (Chair)
- Walter Dean
- Donald Gautier
- Robert Weimer

### SCIENTIFIC SESSIONS:

- Sequence Stratigraphy
  - Dale Leckie
  - Robert Weimer
- Black Shales
  - Walter Dean
  - Lisa Pratt
- Cyclostratigraphy
  - Al Fischer
  - David Bottjer
- Carbonate Platforms
  - Pamela Hallock Muller
  - Erle Kauffman
- Paleogeography/Paleoclimatology
  - Eric Barron
  - Lee Kump
- Poster Sessions
  - Karen Franczyk

### CORE WORKSHOPS:

- Black Shales/Cycles
  - Michael Arthur
  - Walter Dean
  - Al Fischer
  - David Bottjer
  - Charles Savrda
  - Erle Kauffman
  - Don Gautier
- Sequence Stratigraphy
  - Robert Weimer
  - John Warme
  - Karen Porter
  - Peter Vail

### FIELD EXCURSIONS:

- Robert Weimer
- John Warme
- Michael Arthur
- Erle Kauffman
- Lisa Pratt
- Al Fischer

This is an announcement of a Research Conference co-sponsored by SEPM (Society of Economic Paleontologists and Mineralogists) and GSGP (Global Sedimentary Geology Program) and entitled "Cretaceous Resources, Events, and Rhythms (CRER)". This CRER Research Conference will be held in Denver, Colorado on August 24-29, 1990 and will feature a variety of scientific sessions, core workshops and a field excursion that revolve around the Cretaceous world —a global environment that differed greatly from that at present and for much of Neogene-Quaternary. The stipulation of this CRER Research Conference is that significant insight into global sedimentary and environmental processes for a time of contrasting paleogeography, sea level, atmospheric and ocean chemistry and climate can be gained by multidisciplinary study of globally distributed Cretaceous sedimentary sequences. The purposes of the Research Conference are to summarize the progress in research to date, provide insights into the wealth of information on Cretaceous environments retained in the stratigraphic record, and to begin to organize an international research agenda for GSGP-CRER.

CRER is the first project officially sponsored by the Global Sedimentary Geology Program and was selected because of the tremendous potential Cretaceous strata hold for understanding and interpreting the geologic record of substantial global environmental change, the origin and distribution of major mineral and hydrocarbon resources, and the origin of persistent and widespread cyclicity in sedimentary sequences. The project will be conducted through cooperative, international, interdisciplinary studies of trends and events recorded in Cretaceous sedimentary sequences.

The following sections present an overview of the objectives of GSGP and CRER and the objectives and organization of the SEPM-sponsored workshop.

## The Global Sedimentary Geology Program and CRER

The Global Sedimentary Geology Program is the activity of a new Commission of the International Union of Geological Sciences that was established in February, 1987. The stated objectives of GSGP are as follows:

(1) to extend understanding of the history of the earth, surficial processes, the evolution of life, and the biotic influences on earth processes through global-scale research on sediments, sedimentary rocks and their contained organisms and remains;

(2) to improve our ability to find, produce and husband natural resources in sedimentary deposits (water, hydrocarbons, minerals, ores, and building materials); and

(3) to expand and enhance the practice of sedimentary geology through training, exchanges, and cooperative research.

A Program Development Committee consisting of Liu Baojun (PRC), Bernard Beaudoin (France), Keith Crook (Australia), Gerhard Einsele (Germany), Robert Ginsburg (US), Ali M'Rabet (Tunisia), Luis Spalletti (Argentina) and Peter Timofeev (USSR) is responsible for the implementation of research and training outlined in the planning document for GSGP (Report of an International Workshop on GSGP, Miami, FL, 1986).

In June, 1987, the Cretaceous Resources, Events and Rhythms (CRER) project became the first originally sponsored by GSGP. A NATO-sponsored meeting was held in Digne, France in September, 1988, in order to develop "white papers" for each of the 5 major international working groups outlined below. These white papers and background on the Cretaceous will be published in a NATO Advanced Research Workshop volume (Kluwer Academic Publishers, The Netherlands), edited by R. Ginsburg and B. Beaudoin in early 1990.

## The Objectives of CRER and the SEPM-CRER Workshop

The Cretaceous period (ca. 136-66 Ma) of earth history offers a significant opportunity for major contributions to understanding global processes and their variations. Cretaceous marine and terrestrial strata are extremely widespread in outcrop, subcrop and in the ocean basins accessible to scientific drilling. The marine record is particularly complete and extensive because of overall higher sea level and multiple major and minor marine transgressions. The origin of these transgressive and regressive cycles is a puzzle because much of the Cretaceous is thought to have been ice-free and characterized by warm, latitudinally equable climates; therefore, ice-volume changes could not have induced much variation in sea level. The Cretaceous was also a time of unusually rapid sea-floor spreading with associated extensive sea-floor volcanic activity. It is likely, therefore, that most of the changes in sea level were related to this tectonic activity. Smaller-scale cyclicity, now commonly attributed to Milankovitch earth-sun orbital rhythmicity, is ubiquitous and well developed in Cretaceous strata, yet the nature of coupling of presumed orbital variations to sedimentary processes to produce such cycles is poorly understood in contrast to similar Quaternary cycles in which changes in solar insolation are linked to changes in sea level through changes in ice volume. The origins of the supposed warm, equable Cretaceous global climate are equally poorly understood, but presumed to be related to a major expression of a "greenhouse" phenomenon, such as might result from higher rates of volcanic outgassing of carbon dioxide. However, even the warm, equable climate paradigm is being challenged as new data are obtained, at least for some parts of the Cretaceous.

Unravelling and quantifying the record of Cretaceous climate and sea level variations and their causes are major frontiers of earth science. Understanding the modes of ocean circulation and chemistry that accompanied the apparent prevailing warm global climate and overall high sea-level stands of the Cretaceous is also a major challenge. For example, Cretaceous episodes of widespread oxygen deficiency in oceanic deep water masses (termed "Oceanic Anoxic Events" or OAEs) marked by widespread organic, carbon-rich sequences loosely called "black shales", are perhaps manifestations of sluggish deep-water turnover rates and consequent decrease in oxygenation that accompanied the Cretaceous "greenhouse" climate. However, the origin of these OAEs is also controversial and a number of plausible but, as yet untested, hypotheses have been put forth. Because a substantial portion of the World's petroleum resources were sourced by Cretaceous organic, carbon-rich sequences, understanding the origin of these sequences is tantamount to understanding the origin of significant oil resources —discovered and undiscovered. Better understanding of these problems requires a concerted, interdisciplinary effort to study Cretaceous sequences on a global basis on land and in the ocean basins.

The Cretaceous biotic record is also rich in examples of extinction and evolution of marine and terrestrial flora and fauna. Carbonate platforms dominated by rudist bivalves characterized many tropical to subtropical regions of the Cretaceous earth; several apparently global episodes of drowning and demise of these platforms occurred, perhaps linked to rapid rates of sea-level rise and spread of anoxic, nutrient-rich waters to shallow environments. The Cretaceous sedimentary record also provides clues to the origin and rise to prominence of angiosperms, modern grasses, placental mammals, planktonic foraminifers, and diatoms, and to the ultimate demise of giant reptiles, ammonites, rudists and other marine and terrestrial organisms. Providing the explanations for the significant bioevents and substantial changes in global biotic diversity during the Cretaceous is an important contribution that can be made to our understanding of the natural changes that mold the biosphere. Again, interdisciplinary studies of the stratigraphic record will facilitate links between paleobiology and paleonenvironment.

Cretaceous strata also contain major reserves of hydrocarbons, coal, kaolinite and bauxite, manganese and phosphorus. Variable combinations of tectonism and volcanism, atmospheric and ocean chemistry, climate, sea level and sediment supply helped to produce some of the largest phosphorite deposits and hydrocarbon reserves known. Accurate prediction of availability of such resources and understanding of their distribution requires models based on a comprehensive knowledge of the Cretaceous world.

Thus, it is certain that study of the Cretaceous sedimentary record on a global scale will reveal new information and concepts relating to fundamental global processes. Because the Cretaceous world was so different from that at present, an understanding of rates of change and the workings of such a world could produce insights into the potential future global changes as well as provide strategies for better management of resources.

The stated objectives of Project CRER are, therefore:

> ". . . to increase understanding of the sedimentary products and the processes responsible for them during Cretaceous time. This goal will be reached through research that will: 1) test the global synchroneity of various rhythms and events; 2) characterize and explain sedimentary deposits that are widely distributed; 3) analyze the global patterns of resources to better understand controls on their formation and aid in further discovery and development; and 4) seek the inter-connections between processes in the biosphere, hydrosphere, atmosphere and lithosphere. In addition to these overall research objectives, Project CRER will serve as a guide for subsequent GSGP Research Projects and a vehicle for promoting international exchange and training of sedimentary geologists."

GSGP-CRER established five formal research groups to focus on a number of interesting and important aspects of the Cretaceous record. These are:

(1) WG1: Sequence Stratigraphy and Sea Level Changes
(2) WG2: Sedimentation in Oxygen-Deficient Oceans
(3) WG3: Cyclostratigraphy
(4) WG4: Cretaceous Carbonate Platforms
(5) WG5: Paleogeography, Paleoclimatology, Sediment Flux

and two coordinating committees for: 1) Geochronology, and 2) Data Management.

The Society of Economic Paleontologists and Mineralogists (SEPM) has encouraged both GSGP and CRER and convened an *ad hoc* committee to encourage participation in the program by U.S. sedimentologists/stratigraphers. In order to develop a concerted effort in CRER on the part of the U.S. research community, a group (Arthur, Dean, Gautier, Weimer) proposed that SEPM sponsor a Research Conference along a CRER theme. This proposal was approved by the SEPM Research Council, chaired by Sherwood W. Wise, at the annual meeting in June, 1989.

## THE SEPM-SPONSORED RESEARCH CONFERENCE

### Cretaceous Resources, Events, and Rhythms

| | |
|---|---|
| **What:** | Global Sedimentary Geology Program, Cretaceous Resources, Events, and Rhythms (CRER), North American Workshop, sponsored by the Society of Economic Paleontologists and Mineralogists (SEPM) as a Research Conference |
| **When:** | August 20 (Mon.) through August 24 (Fri.), 1990 |
| **Where:** | Denver, Colorado (USGS Core Res. Center, Federal Center & environs) |
| **Why:** | Integrate the activities of the five working groups of CRER (listed below) with a program of formal scientific presentations, discussions of research strategies and programs, core workshops and field excursions. |

1) Sequence Stratigraphy and Sea Level Changes
2) Stratigraphy, Geochemistry and Paleoceanography of Organic Carbon-Rich Sequences
3) Cyclostratigraphy
4) Evolution and Demise of Carbonate Platforms
5) Paleogeography, Paleoclimatology and Sediment Flux

**Who:** Meeting organized by Michael Arthur (URI/GSO), Walter Dean (USGS), Donald Gautier (USGS), and Robert Weimer (Colorado School of Mines) with substantial help from a group of session chairpersons.

## Details

We will hold the 5-day meeting at the Denver Federal Center, Lakewood, Colorado. The main reasons for holding it here are: 1) the Denver-Boulder region is a focal point for studies of North American Cretaceous rocks, a number of potential participants reside in the area, and it is convenient for others living on any coast; 2) reasonable accommodations for attendees and numerous restaurants are located just off the Federal Center; 3) a lecture hall and facilities are available that can accommodate 100+ people; 4) the USGS Core Research Center is located on the Federal Center and will be the focus of several planned workshops; 5) spectacular outcrops of Cretaceous marine and nonmarine strata are located within an easy 1-day round trip; and 6) the conference committee can assure a well-organized and logistically feasible meeting because most live and work there.

Our philosophy is that we want to encourage interdisciplinary work and cross-fertilization in CRER; therefore, we are not planning concurrent sessions. This, of course, limits the number of formal presentations that can be made, but also stimulates interactions among the various working groups, which overlap somewhat in their interests anyway.

The meeting will consist of 5 one-half day sessions featuring formal scientific presentations. One-half day will be devoted to each of the working groups; we have tentatively planned a 40-minute keynote followed by 7, 20-minute talks (and a 20-minute coffee break) for each session. Each session (Working Group) will be chaired by two experts in the field whose responsibility it is to organize the scientific presentations. We also plan to have poster-style presentations over 2 evenings to accommodate everyone who would like to present results of research at the meeting. One other evening will be devoted to informal sessions for each of the working groups, at which time the participants can discuss the goals of participation in GSGP-CRER and scientific objectives as well as possible collaborative research and plans for future field seminars or conferences.

## Workshops

Two half-day sessions will feature 2 separate core workshops. The first (Arthur, Dean, Gautier and others) will display cores of the Greenhorn and Niobrara Formations from the Cretaceous Western Interior seaway of North America, and will primarily involve discussion of sampling, analytical, and interpretive techniques in the study of Milankovitch cycles and organic, carbon-rich strata. The second workshop (Weimer, Vail, Kauffman and others) will focus on sequence stratigraphy and the effects of sea level changes on sedimentation in a Cretaceous epicontinental sea, again using cores, well logs and seismic records from the Cretaceous Western Interior seaway of North America. The main objectives of these workshops are to educate those who are unfamiliar with the principles of analysis and interpretation and to promote discussion of the lithologic, biotic and geochemical features that can be observed in such sequences as well as in geophysical logs. These workshops should encourage interaction between the participants.

The workshops will tie into a planned 1-day field excursion for all participants, which will take in a transect of middle to upper Cretaceous marine clastic and hemipelagic strata from Golden to Pueblo, CO. Field guides and other materials will be assembled for distribution to the participants.

In addition, Working Group 3 will likely sponsor a 2-day, post-conference short course for its members (Cyclostratigraphy) and other interested participants in "Numerical Methods for Spectral and Time-Series Analysis". Such plans are tentative at this time, but would help take advantage of the investment in travel that will have been made.

## Field Excursions

The field excursion will feature a one-day trip along the Colorado Front Range (led by R. Weimer, M. Arthur,

L. Pratt, and E. Kauffman) in order to examine: 1) sequence stratigraphy in the lower Cretaceous (mainly Albian) clastic sequences along the Front Range between Golden and Morrison; 2) sequence stratigraphy and cyclicity of the Cenomanian-Turonian Hartland Shale-Bridge Creek Limestone units and the Turonian-lower Coniacian Fort Hays Limestone and lower Smoky Hill Shale members of the Niobrara Formation near Pueblo; and 3) "tepee buttes" of the Campanian (Upper Cretaceous) Pierre Shale near Pueblo —fascinating carbonate mounds and unique Cretaceous seafloor faunas associated with submarine venting of methane-charged fluids in a relatively shallow-marine setting.

There is nothing in the way of a Cretaceous carbonate platform nearby, but it is possible that Hallock and Kauffman will organize a pre- or post-conference trip to examine some spectacular sequences exposed in Mexico for the members of Working Group 4.

## Conference Expenses

The registration fee for the SEPM Research Conference is $195. This fee covers the basic costs of running the conference, including: fees for exhibit space and projection equipment, all coffee breaks and lunches, guidebooks and other handouts, bus transportation and meals on the field excursion, insurance, etc. Lodging and some meals are not included in the fee. However, a government rate has been obtained for rooms at the Compri Hotel, which is within walking distance of the Federal Center, and a block of rooms has been reserved for conference participants. The room rate ($65 for single, $75 for double, tax incl.) at the Compri includes breakfast.

## Registration

Interested researchers should apply to SEPM directly at the following address to register for the conference:

S.E.P.M.
P.O. Box 4756
Tulsa, OK 74159-0756

or call Ms. Susan Green at (918) 743-9765 for further information. All registrants will be sent a second meeting package in early August.

## Hotel

At such time as your registration for the conference is approved, you should reserve your room at the Compri Hotel at the number below. Refer to "block code" #819USG.

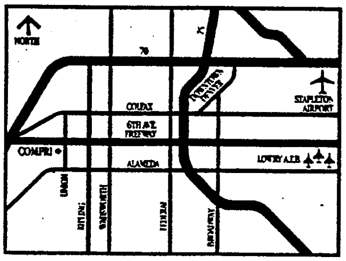
Compri Hotel
Denver West
Lakewood

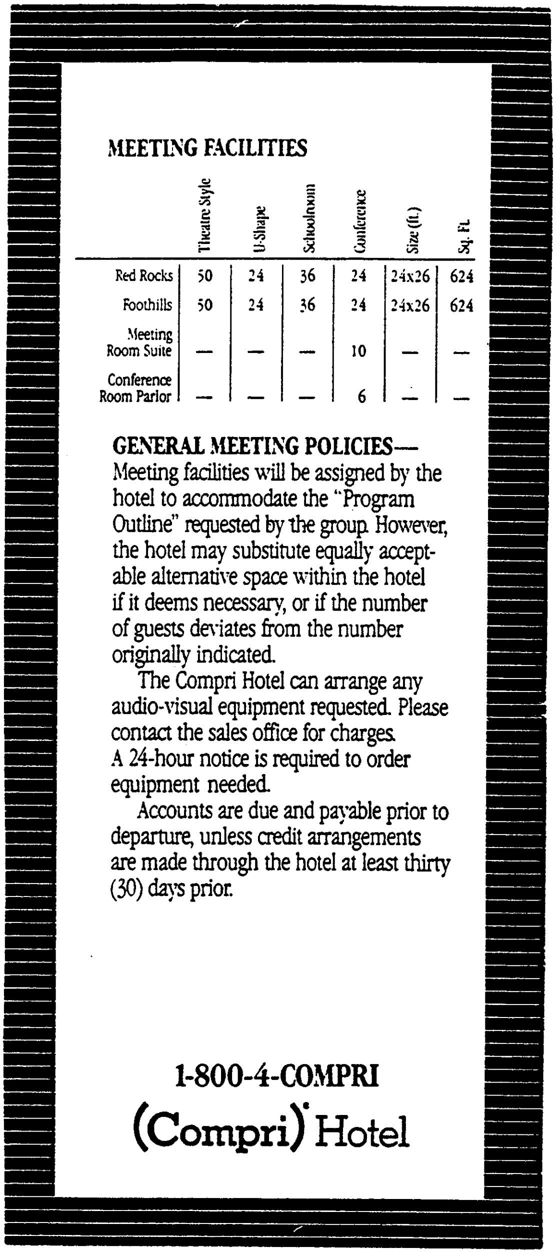
303-969-9900

**LOCATION**—Situated in the foothills of the Rockies. In Lakewood, 7 miles west of downtown Denver, near the intersection of the 6th Avenue Freeway and Union Boulevard. 137 Union Boulevard, Lakewood, CO 80228. (Union at 6th Avenue.)

**NEARBY POINTS OF INTEREST**—Coors Brewery (7 miles), historic downtown Denver (7 miles), Red Rocks Park (5 miles) and major ski areas (60 miles). Also near COBE Lab (2 miles), Rocky Mountain Bank Note (1 mile), American Management Systems (1 mile), Denver Federal Center (1 block) and the National Park Service (1 mile).

**AMENITIES**—170 rooms. Full, cooked-to-order breakfast, hosted Director's Reception and late night snacks included in the rate. Outdoor pool, in-room pay movies, whirlpool and complete work-out facilities. Light dinners available in the Club.





MEETING FACILITIES

| | Theatre Style | U-Shape | Schoolroom | Conference | Size (ft.) | Sq. Ft. |
|---|---|---|---|---|---|---|
| Red Rocks | 50 | 24 | 36 | 24 | 24x26 | 624 |
| Foothills | 50 | 24 | 36 | 24 | 24x26 | 624 |
| Meeting Room Suite | — | — | — | 10 | — | — |
| Conference Room Parlor | — | — | — | 6 | — | — |

**GENERAL MEETING POLICIES—** Meeting facilities will be assigned by the hotel to accommodate the "Program Outline" requested by the group. However, the hotel may substitute equally acceptable alternative space within the hotel if it deems necessary, or if the number of guests deviates from the number originally indicated.

The Compri Hotel can arrange any audio-visual equipment requested. Please contact the sales office for charges.

A 24-hour notice is required to order equipment needed.

Accounts are due and payable prior to departure, unless credit arrangements are made through the hotel at least thirty (30) days prior.

1-800-4-COMPRI

(Compri)® Hotel

### Funds to Defray Travel Costs for Participants

We are attempting to obtain funding in order to encourage attendance by graduate students and to help other participants with the costs of travel. Our main objective is to develop interest in problems of Cretaceous earth history on the part of a talented pool of graduate students and other scientists, some as yet uninitiated in Cretaceous research, who will possibly pursue research topics in this area. The availability of these travel funds will be advertised in *Geotimes* and *EOS*, as well as in a mailing to known Cretaceous enthusiasts.

The Research Conference would be of great value to graduate students (and other young scientists) in career development because of : 1) contacts with a variety of experts in aspects of Cretaceous stratigraphy and paleoenvironments; 2) exposure to interdisciplinary approaches to research; 3) the opportunity to steep themselves in the latest hypotheses and data for a number of aspects of Cretaceous sedimentary regimes, paleoclimatology, sea level changes and the like; 4) the opportunity to present results of their research to a receptive and knowledgeable audience who could provide substantial feedback to them; and 5) workshops and field excursions will be geared to training in approaches to study of sedimentary sequences in general, but with the U.S. western interior Cretaceous system as an example.

### Graduate Student "Travel Grants"

We will limit the SEPM Research Conference to 100 scientific participants. Of this total we hope to have at least 10 to 15 graduate students in attendance. In order to encourage them to attend, we hope to offer about 10 "travel grants" of $645 each to qualified graduate students. (This is dependant upon receiving extramural support for the meeting.) This amount would cover airfare and registration for the meeting or some combination of airfare, hotel, and registration. We (the organizing committee, with advice from session chairpersons) will select the students on the basis of a simple application in which they will be asked to provide a brief, 1-page description of their thesis research objectives, a statement as to why they would like to attend the Research Conference, and a budget of realistic travel costs (i.e., airfare, because we already know the costs for registration and hotel). Some preference will be given to those who would present a poster session or talk on their research at the Research Conference. If a larger number than 10 qualified graduate students apply, we will most likely attempt to spread the resources amongst all of them, but with a minimum of $450 per student (*for example: a double* *room for 6 nights would cost $225 at the Conference rate, leaving an additional $225 for airfare or for meals and conference registration*). These students will be encouraged to book excursion coach fares with one Saturday night stay in order to keep costs down. We will prepay airline tickets, hotel and/or registration for them, as appropriate, in order to minimize the paperwork for travel advances and accounting.

### Funds for Other Participants

We are requesting additional funds for partial support of a number of other participants, particularly key speakers and/or session chairpersons who could not otherwise attend. We plan to limit these awards to about $400, which would allow partial support of at least 8 scientists. Again, we will advertise availability of these funds and request applications for support which will be acted upon by the organizing committee. As stated above, these funds are important to assure that we can attract key participants to the Research Conference in order to make the scientific sessions of the highest quality. We are not, however, assured of meeting our objectives. The status of such funds will be known by **April 1, 1990.** Details will be provided in the Second Circular at that time. Requests should be sent directly to:

Michael A. Arthur
Graduate School of Oceanography
University of Rhode Island
Narragansett, RI 02882-1197
(401) 792-~~6268~~ or 6709
6867

### Call for Papers

The Convenors of scientific sessions have been charged with developing a series of oral presentations for their sessions. Because of time constraints, we anticipate that poster sessions will be a very effective means of presenting research results. Individuals are encouraged to contact session leaders directly if they desire to present a talk or poster. The requisite addresses' and phone numbers are attached.

## SESSION CONTACTS

### Sequence Stratigraphy

Dr. Dale A. Leckie
Inst. of Sed. & Petroleum Geology
Geological Survey of Canada
3303 - 33rd St., NW
Calgary, Alberta T2L 2A7
CANADA
(403) 284-0110

Dr. Robert Weimer
Colorado School of Mines
Dept. of Geology & Engineering
Golden, CO 80401
(303) 526-0247

### Black Shales

Dr. Walter E. Dean
U.S. Geological Survey, MS 939
Federal Center
Denver, CO 80225
(303) 236-5760/1644

Dr. Lisa M. Pratt
Dept. of Geology
Indiana University
Bloomington, IN 47405
(812) 855-9203

### Cyclostratigraphy

Dr. Alfred G. Fischer
Geological Sciences
University of Southern California
University Park
Los Angeles, CA 90089-9741
(213) 547-5220

Dr. David J. Bottjer
Geological Sciences
University of Southern California
University Park
Los Angeles, CA 90089-9741
(213) 743-8913

### Carbonate Platforms

Dr. Pamela Hallock Muller
Dept. of Mar. Science
University of Southern Florida
140 7th Ave., South
St. Petersburg, FL 33701
(813) 893-9567

Dr. Erle G. Kauffman
Dept. of Geol. Sciences CB-250
University of Colorado
Boulder, CO 80309
(303) 492-6629

### Paleogeography/Paleoclimatology

Dr. Eric J. Barron
Earth System Science Center
Pennsylvania State University
University Park, PA 16802
(814) 865-1619

Dr. Lee Kump
Earth System Science Center
Pennsylvania State University
University Park, PA 16802
(814) 863-1274

### Poster Sessions

Karen Franczyk
U.S. Geological Survey, MS 939
Federal Center
Denver, CO 80225
(303) 236-5566

# *PROGRAM*

## MONDAY Morning, Aug. 20: *"Sequence Stratigraphy and Sea Level Change"*

Location: Bldg. 20 (R. Weimer and D. Leckie)

| | | |
|---|---|---|
| 8:30 – 9:10 | | Introduction to Workshop, M. Arthur & W. Dean |
| 9:10 – 9:50 | (Keynote) | R. Weimer |
| 9:50 – 10:20 | | D. Leckie |
| 10:20 – 10:40 | | J. Dixon |
| 10:40 – 11:00 | | *Coffee Break* |
| 11:00 – 11:20 | | T. Ryer |
| 11:20 – 11:40 | | S. Ferry |
| 11:40 – 12:00 | | P. Vail |
| 12:00 – 1:10 | | *Lunch* |

Program of Oral Presentations: (*Speaker)

| | | |
|---|---|---|
| 1. | R.J. Weimer* | "Western Interior Cretaceous Project (WIK) and Sequence Stratigraphy" |
| 2. | D. Leckie* | "The Effects of Middle to Late Albian Sea Level Fluctuations in the Peace River Formation of Western Canada: Incised Valleys, Paleosols, Estuaries and Shallow-Water Condensed Sections" |
| 3. | J. Dixon* | "Sequences in Cretaceous Strata of Northwest Canada: Tectonic or Eustatic?" |
| 4. | T.A. Ryer* | "Relative Importance of Fluxuations in Sea Level and Sediment Supply in the Origin of Mid-Cretaceous Clastic Wedges, Central Rocky Mountain Region" |
| 5. | S. Ferry* | "Sequence Stratigraphy in Open-Margin Deep-Water Carbonates (Mesozoic, French Alps), Comparison with Silled Basins" |
| 6. | P. Vail* | "Sequence Stratigraphy of the Cretaceous" |

## MONDAY Afternoon, Aug. 20: *"Cyclostratigraphy"* (A. Fischer and D. Bottjer)

Location: Bldg. 20

| | | |
|---|---|---|
| 1:10 – 1:50 | (Keynote) | T. Herbert |
| 1:50 – 2:10 | | E. Gustason et al. (given by B. Sageman) |

| | |
|---|---|
| 2:10 - 2:30 | W. Ross et al. |
| 2:30 - 2:50 | M. Arthur et al. |
| 2:50 - 3:10 | *Coffee Break* |
| 3:10 - 3:30 | C. Savrda and D. Bottjer |
| 3:30 - 3:50 | E. Erba (Premoli Silva and Erba) |
| 3:50 - 4:10 | H. Zijlstra |
| 4:10 - 4:30 | J. Park and R. Oglesby |
| 8:00 pm | Joint Meeting CRER Research Planning (general); all 5 working groups at Compri Hotel (Foothill Room) |

Program of Oral Presentations: (*Speaker)

1. T. Herbert* "The Orbital Beat: Key to High Resolution Paleoclimatic and Paleoflux Studies in the Cretaceous"

2. E. Gustason, W.P. Elder, and B.B. Sageman* "Correlation of Small-Scale Sedimentary Cycles from Basin to Strandline, Greenhorn Cyclothem, Western Interior, U.S."

3. W.C. Ross*, J.E. May, and D.A. Watts "Reconstructing Depositional Geometries and Interpolating Age Information at the Parasequence Scale"

4. M.A. Arthur*, W.E. Dean, and L.M. Pratt "Geochemical Expression of Milankovitch Cycles in Cretaceous Pelagic Marine Strata of the Western Interior Seaway"

5. C.E. Savrda* and D.J. Bottjer "Trace-Fossil Record of Redox Cyclicity in the Niobrara Formation"

6. I. Premoli-Silva and E. Erba* "Orbitally Driven Cycles in Trace Fossil Distribution from the Piobbico Core (Late Albian, Central Italy)"

7. J.J.P. Zijlstra* "Rhythmic Bedding of Depositional Structures and Early Diagenetic Mineralization in the Chalk of the Maastrichtian Type Locality"

8. J. Park* and R.J. Oglesby
"The Effect of Precession and Obliquity on Cretaceous Climate and Cyclic Sedimentation: A GCM Modeling Study"

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**TUESDAY Morning, Aug. 21:** *"Organic-Carbon-Rich Sequences"*
Location: Bldg. 20 (W. Dean and L. Pratt)

| | |
|---|---|
| 8:30 - 9:10 (Keynote) | T. Loutit et al. |
| 9:10 - 9:30 | B. Sageman and E. Kauffman |
| 9:30 - 9:50 | H. Brumsack |
| 9:50 - 10:10 | L. Pratt |
| 10:10 - 10:30 | *Coffee Break* |
| 10:30 - 10:50 | T. Pederson and S. Calvert |
| 10:50 - 11:10 | T. Bralower et al. |
| 11:10 - 11:30 | W. Sliter |
| 11:30 - 11:50 | W. Dean et al. |
| 11:50 - 1:10 | *Lunch* |

Program of Oral Presentations: (*Speaker)

1. T.S. Loutit*, A.E. Bence, F.B. Zelt, and W.J. Devlin
"Processes Controlling the Deposition of the Sharon Springs Member of the Pierre Shale During the Early Campanian"

2. B.B. Sageman* and E.G. Kauffman
"High Resolution Paleoecological Reconstruction of Cretaceous Black Shale Facies"

3. H.J. Brumsack* "Trace Metals in Cretaceous Black Shales"

4. L.M. Pratt* "Organic Geochemical Indicators of Productivity vs. Preservation of Organic Matter in Cretaceous Black Shales"

5. T.F. Pederson* and S.E. Calvert
"Oxygen Minima and Organic-Rich Sediments: Is There a Causative Relationship?"

6. T.J. Bralower*, R.M. Leckie, W.V. Sliter, D. Allard, M. Arthur and S.O. Schlanger
"Oceanwide Anoxia in the Early Aptian"

7. W.V. Sliter* "Biochronology and Biologic Characterization of Aptian to Turonian Organic-Rich Sequences"

8. W.E. Dean*, M.A. Arthur, and L.M. Pratt
"Geochemical Evidence for Global Changes in Organic-Carbon Burial and Paleoceanography at the Cenomanian/Turonian Boundary"

<u>TUESDAY Afternoon, Aug. 21</u>:
<u>Location</u>: Bldg. 810

| | |
|---|---|
| 1:10 - 4:30 | Core Workshop I: *"Cyclostratigraphy, Sequence Stratigraphy and Black Shales of the Cretaceous Western Interior"* (see later description) |
| 4:30 - 6:30 | Poster Session |

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<u>WEDNESDAY, Aug. 22</u>:

| | |
|---|---|
| 8:00 am – 11:30 pm | Field Trip and Barbeque (buses will depart Compri Hotel at 8:00 am) |

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<u>THURSDAY Morning, Aug. 23</u>: *"Carbonate Platforms"*
<u>Location</u>: Bldg. 20 (E. Kauffman and P. Hallock)

| | |
|---|---|
| 8:30 - 9:10 (Keynote) | R.W. Scott |
| 9:10 - 9:30 | W.W. Hay et al. |
| 9:30 - 9:50 | P. Hallock |
| 9:50 - 10:10 | C.C. Johnson |
| 10:10 - 10:30 | *Coffee Break* |
| 10:30 - 10:50 | E.L. Winterer and R. Vanwaasbergen |
| 10:50 - 11:10 | E.G. Kauffman |
| 11:10 - 11:30 | G. Camoin |
| 11:30 - 11:50 | G. Koutzoukos |
| 11:50 - 1:10 | *Lunch* |

<u>Program of Oral Presentations</u>:

1. R.W. Scott* "Models of Cretaceous Carbonate Platforms in the Caribbean Province"

2. W.W. Hay*, C.N. Wold, and K.M. Wilson
"Cretaceous Reefs and Paleo-Ocean Circulation"

3. P. Hallock* "Nutrient Flux as a Regulating Mechanism for Reef Development: Modern and Cretaceous Models"

4. C.C. Johnson* "Cretaceous Paleobiogeography of Rudist Bivalves and Reef Ecosystems in the Caribbean Province"

5. E.L. Winterer* and R. Vanwaasbergen "Emergence and Karsting of Pacific Mid-Cretaceous Guyots, the Birth of the Darwin Rise, and Global Sea Level"

6. E.G. Kauffman* "Temporal and Spatial Distribution of Cretaceous Reef Communities on Carbonate Platforms of the Caribbean Province"

7. G.F. Camoin* "Coral-Dominated Frameworks Across Cretaceous Carbonate Platforms"

8. E. Koutsoukos* "Foraminiferal Distribution Patterns and Controlling Mechanisms Across Mid-Cretaceous Carbonate Shelves from Low-Latitude Western Atlantic Regions"

**THURSDAY Afternoon, Aug. 23:**
Location: Bldg. 810

| | |
|---|---|
| 1:10 – 4:30 | Core Workshop II: *"Sequence Stratigraphic Concepts and Sea Level"* (see later description) |
| 4:30 – 6:30 | Poster Session |
| 8:00 – 11:00 | Ocean Drilling Program Objectives Meeting at Compri Hotel (Foothill Room) |

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**FRIDAY, Morning, Aug. 24:** *"Paleogeography, Paleoclimatology, and Sediment Flux"*
Location: Bldg. 20 (E. Barron and L. Kump)

| | |
|---|---|
| 8:30 – 9:10 (Keynote) | E.J. Barron |
| 9:10 – 9:30 | J.T. Parrish and R. Spicer |
| 9:30 – 9:50 | M. Leckie et al. |
| 9:50 – 10:10 | G. Bluth and L.R. Kump |
| 10:10 – 10:30 | *Coffee Break* |
| 10:30 – 10:50 | R.L. Larson |
| 10:50 – 11:10 | T. Glancy |
| 11:10 – 11:20 | R. Slingerland |
| 11:30 – 11:50 | W. Elder |

Program of Oral Presentations:

1. E.J. Barron* "Cretaceous Global Climate Reconstruction"

2. J.T. Parrish* and R.A. Spicer
"Cretaceous Non-Marine Climate Reconstruction, with Emphasis on Polar Regions"

3. M. Leckie*, D. Finkelstein, R. Yuretich, M. Schmidt, D. West and C. Hayden
"Paleoceanography and Paleoclimatology of the Cretaceous Western Interior Seaway: Marriage of Foraminiferal Paleoecology and Clay Mineralogy"

4. G.J.S. Bluth and L.R. Kump*
"Paleogeology of the Cretaceous and its Implications for Carbon Dioxide and Climate"

5. R.L. Larson* "The Earth's Ocean Crustal Production, 0–150 m.y.: Evidence for a Mid-Cretaceous 'super plume'"

6. T. Glancy* "Computer Climate Sensitivity Studies of Milankovitch-Scale Insolation Variations on the Cretaceous Western Interior Seaway"

7. R. Slingerland* "Numerical Simulation of the Ocean Circulation in the Cretaceous Western Interior Seaway"

8. W.P. Elder* "Paleoclimatic and Oceanographic Implications of Cretaceous Faunal Distributions in the Western Interior Seaway"

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## POSTER PRESENTATIONS

### *Sequence Stratigraphy*

1. Banerjee, I. "Sequence Stratigraphy of the Mannville Group, Southern Alberta, Canada"

2. Bergen, J.A., M.J. Evetts, P.C. Franks, M.D. Lewan, R.W. Scott, and J.A. Stein
"Mid-Cretaceous Sequences and Cyclostratigraphy, Western Kansas"

3. Bloch, J., D.A. Leckie, J. Wall, C. Schroeder-Adams, C. Singh, and M. Wilson
"Marine Shales of Albian to Turonian Colorado Group, Wester Canada: Sedimentology, Geochemistry and Paleontology —Prelminary Results"

4. Bowman, S.A. and P.R. Vail
   "Sequence Stratigraphy of the Albian-Santonian of Colorado and Wyoming"

5. Haerter, J.P. and F.G. Ethridge
   "Sequence Stratigraphy, Lower Cretaceous, Fall River Sandstone, northern Powder River basin, Wyoming and Montana"

6. Hettinger, R.D. and P.J. McCabe
   "Systems Tract Development Associated with a Major Marine Transgression —The mid-Cretaceous of the Kaiparowits Plateau, Utah"

7. Jacquin, T., C. Ravenne, and P. Vail
   "The Effects of Transgressive/Regressive Facies Cycles on the Stratal Pattern of Systems Tracts: The Barremian-Aptian Platform-Basin Transition in the Vercors (Northern Sub-Alpine Chains, France)

8. Kirschbaum, M.A. and P.J. McCabe
   "Variations in Alluvial Architecture in a Transgressive Systems Tract, Dakota Formation, Utah"

9. Leckie, D.A. and K.W.-Dudley
   "Heirarchical and Retrogradational, Low-stand-Shelf Sandstones Below Condensed Section in the Lower Kaskapau Formation (Upper Cenomanian-Lowest Turonian), Alberta, Canada"

10. Reinson, J., W.J. Warters, and P.R. Price
    "Stratigraphic Sequences in the Viking Formation South-Central Alberta, Canada"

11. Weimer, R. and B. Bruce
    "Example of WIK Reference Section Data Base"

*Cyclostratigraphy*

1. Cotillon, P. "Time Measurement and Correlations by High-Frequency Sedimentary Cycles: Limits of Methods"

2. D'Argenio, B., V. Ferreri, M. Iorio, and B. Longo
"Peritidal Cyclicity in the Milankovitch Band: Barremian Carbonate Deposits of Monte Maggiore (Southern Apennines, Italy)"

3. Erba, E., D. Castradori, and G. Guasti
"Paleofertility Milankovitch Cycles in Calcareous Nannofossil Assemblages: Evidence from the Albian Gault Clay Formation"

4. Rampino, M.R. "Long-term Rhythms in the Mesozoic: Tectonics, Sea Level, Ocean Circulation, and Climate"

5. Thurow, J., P. Bitschene, H.-J. Brumsack, E. Kemper, R. Littke, J. Mutterlose, M. Prauss, W. Riegel, J. Rullkötter, H.-U. Schmincke, R. Stein, E. Usdowski, and J. Wiedmann
"Sedimentary, Biotic and Geochemical Cycles in the Boreal Cretaceous: Introducing a Multi-Disciplinary Drilling Project in Northern Germany (The Boreal Cretaceous Cycles Project - BCCP)"

### *Organic-Carbon-Rich Sequences*

1. Bloch, J. "Fluid- and Rock-Dominated Sulfide Diagenesis of the Albian Harmon Member, Western Canada"

2. Erba, E. and F. Lottaroli
"Timing and Paleoceanography of Aptian-Albian Anoxic Events from Italian Sequences: The Contribution of Calcareous Nannofossils"

3. Suits, N. and L.M. Pratt
"Sulfur Isotopic Excursion at the Cenomanian-Turonian Boundary Recorded by Pyrite and Acid-Volatile Sulfides"

### *Carbonate Platforms*

1. Viviera, M.C. "Paleoenvironmental Assessment of Microfossil Assemblages Associated with Late Cretaceous Carbonates and Phosphorites in the Potiguar Basin, North Brazil"

## *Paleogeography and Paleoclimatology*

1. Barrera, E. "$\delta^{18}O$, $\delta^{13}C$ and $^{87}Sr/^{86}S$ Trends in Maastrichtian Foraminiferal Sediments from the Southern Oceans"
2. Barrera, E. and G. Keller
   "Late Maastrichtian to Early Tertiary Environmental Conditions Near Brazos River, Texas: Foraminiferal Stable Isotope Evidence"
3. Caldeira K. and M.R. Rampino
   "Carbonate-silicate Cycle Modeling at the Cretaceous/Tertiary Boundary"
4. Deconto, R.M. and W.W. Hay
   "The Source of Cretaceous Detrital Sediment in the Western North Atlantic"
5. Dettman, D.L. and K.C. Lohmann
   "Isotopic Variability in Maastrichtian Freshwater Bivalves: a Measurement of Environmental Change on Weekly, Monthly, and Eearly Time Scales"
6. Föllmi, K.B. "Mid-Cretaceous Phosphatic Sediments Along the Northern Tethyan Margin: Documents of Explicit Nonlinear Sedimentary and Environmental Dynamics"
7. Huber, B.T. "Circum-Antarctic Paleobiogeography of Campanian-Maastrichtian Foraminifera: Implication for Paleogeographic and Paleoceanographic Reconstructions"
8. Uliana, M.A., L. Legarreta, G. Peroni, H.A. Leanza, and A. Gutierrez Pleimling
   "Paleogeographic Distribution of Later Hauterivian-Early Barremian Sequences of Neuquen Basin, Argentina"
9. Leithold, E.L. "Fine-grained Sediment Dispersal Along the Western Margin of the Cretaceous Interior Seaway, Southern Utah"

10. Merewether, E.A. and D.L. Gautier
"Stratigraphic, Petrologic, and Paleontologic Evidence for a Brackish, Restricted Seaway in Early Cenomanian (Mid-Cretaceous) Time, Eastern Wyoming"

11. Park, J. and R.J. Oglesby
"The Effect of Precession and Obliquity on Cretaceous Climate and Cyclic Sedimentation: A GCM Modeling Study"

12. Wold, C.N. and W.W. Hay
"The Cretaceous South Atlantic Lakes and Their Water Source"

*Lecture Hall Display*

1. Scotese, C.R. "Cretaceous Plate Tectonic Reorganizations: Mechanism for Global Change"

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## EVENING RESEARCH PLANNING SESSIONS

One of our important objectives in gathering such an august group of experts together is to encourage development of research programs under the auspices of the GSGP/CRER Program. R.N. Ginsburg, Chair of GSGP, will be in attendance. There will therefore be two scheduled sessions in which interested participants should take the opportunity to present and discuss possible approaches to global-scale or regional research on one or more CRER topics. Several groups have already expressed an interest in presenting proposals for discussion. There are two evening sessions planned at present as follows. The sessions will be held in the Red Rocks and/or the Foothills Rooms at the Compri Hotel. Contact the the individuals below for more information:

Mon., Aug. 20, 8-11pm: CRER Research Planning Meeting
Contact: A.G. Fischer (213-743-3420 or 213-547-5220)

Thurs., Aug. 23, 8-11pm: Ocean Drilling Program Objectives
Contact: M.A. Arthur (401-792-6867)

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## *TUESDAY Afternoon, Aug. 21: Core Workshop I and Poster Sessions*

Core Workshop I: 1:10 – 4:30pm (U.S.G.S. Core Research Center, Bldg. 810)
Poster Sessions*: 4:30 – 6:30pm (Refreshments will be served)

### *Core Workshop I: Cyclostratigraphy, Sequence Stratigraphy and Black Shales of the Western Interior Seaway*

***Hosts and Discussants:***

***W.E. Dean, M.A. Arthur, L.M. Pratt, A.G. Fischer, C. Savrda, D. Bottjer, E.G. Kauffman, D.L. Gautier (with additional contributions/displays by R.W. Scott et al., T. Loutit and F. Zelt)***

This will be a reasonably freeform workshop featuring displays and core material from wells in Colorado and Kansas. Cores of parts of the Greenhorn and Niobrara cyclothems will be exhibited along with available stratigraphic and geochemical data. The workshop will focus on discussion of sampling strategies, techniques of study and interpretation of lithologic, geochemical and biotic trends across Milankovitch-scale cycles, black shales and other features. There will be ample time for detailed examination of cores, if desired, and participants will be encouraged to discuss or question interpretations offered by the session leaders.

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***See poster session list and abstracts.**

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## *WEDNESDAY, Aug. 22: Field Excursion*

### *Dakota Sequence Stratigraphy, Colorado Front Range near Denver*
### *&*
### *Cycles and Black Shales, Rock Canyon near Pueblo*

Logistics

- Buses will depart from entrance to Compri Hotel at 8:00 am sharp.
- A box lunch will be furnished en route.

- Participants will receive a supplementary field trip guide and SEPM Field Trip Guide #4.
- The trip will culminate with a Barbeque, refreshments and entertainment at the North marina overlooking Pueblo Reservoir and the Rock Canyon sequence.
- Buses will return to Compri Hotel by about 11:30 pm.

Remember, the temperature in the Pueblo area could be in excess of 100°F; dress to keep cool and bring some headgear to protect you from the intense August sun. However, you should also carry a light jacket because temperatures can plummet in the evening or during possible thunder storms.

Geologic Features

*Morning:* *Sequence Stratigraphy and Depositional Environments of the Dakota Group in the Golden-Morrison Area*
*Leaders:* *R. Weimer and J. Warme*

Participants will have the opportunity to observe outcrops of the Dakota Group (I-70; Alameda, and Turkey Creek cuts) and to discuss sequence stratigraphic concepts. Unconformities (sequence boundaries) that formed during sea-level lowstands and related incised valley fills are separated by marine shales and sandstones formed during highstands.

*Afternoon:* *Mid-Cretaceous Cycles, Black Shales and Sequence Stratigraphy in the Pueblo Area and Late Cretaceous Submarine Vent Deposits*
*Leaders:* *E.G. Kauffman, M.A. Arthur, L.M. Pratt, A.G. Fischer, and W.E. Dean*

Participants will first have the opportunity to examine unique biotic and petrologic features of "Teepee Buttes" in the Pierre Shale near Boone, Colorado —deposits associated with submarine venting of methane-rich fluids. The remainder of the afternoon will be spent in Rock Canyon west of Pueblo, examining outcrops of the Graneros shale (lower Cenomanian) through Fort Hays Limestone mbr (upper Turonian) of the Niobrara formation. Various aspects of sequence stratigraphy, cyclostratigraphy and black shale deposition will be discussed.

## *THURSDAY Afternoon, Aug. 23: Core Workshop II and Poster Sessions*

| | | |
|---|---|---|
| Core Workshop II: | 1:10 – 4:30 pm | (U.S.G.S. Core Research Center, Bldg. 810) |
| Poster Sessions*: | 4:30 – 6:30 pm | (Refreshments will be served) |

*Core Workshop II: Sequence Stratigraphic Concepts and Sea Level: Examples from the Cretaceous Muddy Sandstone*

*Hosts and Discussants: R. Weimer, F. Ethridge, J. Dolson, M. Chapin, K. Porter and J. Warme*

This workshop features depositional facies in cores and inferences from geophysical logs from the Denver Basin and adjacent areas along with discussion of unconformities and the role of sea level changes. Sequence stratigraphic concepts will be illustrated by cores largely from the lower Cretaceous Muddy sandstone. The format will include lectures, video, core layouts, displays and exercises. There will be ample time for discussion, questions and detailed examination of the cores.

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***continuation of posters from Tuesday**

# *ABSTRACTS*

# SEQUENCE STRATIGRAPHY OF THE MANNVILLE GROUP, SOUTHERN ALBERTA, CANADA

**BANERJEE, I.**
Geological Survey of Canada, 3303-33rd St., NW, Calgary, Alberta, T2L 2A7
CANADA

Integration of a large amount of subsurface data has resulted in a sequence stratigraphic model for the Lower Cretaceous (Barremian to Middle Albian) Mannville Group, which consists of 100 to 200 m of non-marine, marginal marine and shallow marine siliciclastic sediments. The Mannville Group is bounded by two regional unconformities that cover most of Alberta Saskatchewan.

The Pre-Mannville surface below the basal unconformity cuts into rocks varying in age from Jurassic to Devonian. Incised paleovalleys occur on this surface. Incised valley-fill deposits vary from marginal marine (Ellerslie Member) to non-marine (Cutbank/Sunburst members).

The upper unconformity is overlain by either the Joli Fou Shale, or the locally developed Basal Colorado Sandstone occupying shallow scours. Although the upper unconformity locally shows incised valley fills, it is generally more subtle with concentrations of granule conglomerates containing phosphate and glauconite grains.

The maximum flooding surface (mfs) in the Mannville sequence can be recognized within the Ostracode Zone member which represents the transgressive systems tract by the occurrence of thin limestones locally containing submarine hardgrounds and organic-rich black shales with high-diversity, open-marine dinoflagellates. Asymmetric shallowing upward cycles 2 to 3 m thick, with molluscan shell concentrations at the base or the end of the cycles, are interpreted as parasequences within the Ostracode Zone.

Overlying the mfs is the highstand systems tract, the lower part of which shows a parasequence set with northward-prograding downlapping surfaces (Glauconitic Sandstone). The upper part shows another parasequence set of aggrading coal cycles.

# MID-CRETACEOUS SEQUENCES AND CYCLOSTRATIGRAPHY, WESTERN KANSAS

Bergen, J.A.[1], M.J. Evetts[1], P.C. Franks[1], M.D. Lewan[2], **R.W. SCOTT**[2], and J.A. Stein[2]
[1]Howard Green Co., Cedar Rapids, IA USA
[2]Amoco Production Company, Tulsa, OK 74102 USA

The middle Cretaceous section in western Kansas has been cored continuously from the base of the Purgatoire Formation to the middle part of the Smoky Hill Member of the Niobrara Formation. This section records several sea-level changes that influenced the development of depositional sequences within the Western Interior Seaway. Chronostratigraphy of this section has been calibrated by means of multidisciplinary fossil groups. Nannofossils, dinoflagellates, spore and pollen, foraminifers, and mollusks have been graphed to a global composite standard containing key reference sections. The age of the base of the Cretaceous section sequence boundary is 100.35 Ma; the base of the Dakota sequence boundary is between 99.1 and 97.4 Ma; and the sequence boundary between the Codell Sandstone Member and the Niobrara Formation is between 89.7 and 88.8 Ma. The Albian-Cenomanian contact as defined in the French reference section correlates approximately with a ravinement surface in the upper part of the Dakota Formation.

The facies and fossils define changing water mass conditions within the Graneros, Greenhorn and Carlile formations. The abundance and diversity of foraminifers, dinoflagellates and nannofossils indicate that the sea water of the Graneros was more oxygen poor and shallower than waters of the Greenhorn. Shoaling conditions returned during deposition of the Codell. The Fort Hays Limestone Member of the Niobrara represents a relatively deep, clear open seaway with abundant and diverse planktic foraminifers.

The Cenomanian-Turonian boundary is defined by nannofossils, dinoflagellates, foraminifers, and organic geochemical features. It falls within the basal part of the Bridge Creek Limestone Member of the Greenhorn. Limestone-marl cycles and sporadic black, calcareous shale beds correspond with the biotic evidence for this contact.

Stable carbon isotopes of kerogen isolated from calcareous black shale in a 5 ft- (1.5 m) thick interval shows a gradual depletion in $^{13}C$ from the Cenomanian to Turonian with a mean delta $^{13}C_{pdb}$ of $-24.5 \pm 0.6\ ^{o}/_{oo}$. Kerogen in the Cenomanian section 6.5 ft- (2 m) thick is $-23.5 \pm 0.2\ ^{o}/_{oo}$, and kerogen from the Turonian section 7 ft- (2.1 m) thick is $-25.7 \pm 0.2\ ^{o}/_{oo}$. Amount of organic carbon and type of kerogen (amorphous type-II) across this interval are essentially the same with minor variations having no relationship with the isotopic shift.

The isotopic shift may be a result of variations in the source of $CO_2$ utilized by phytoplankton in the euphotic zone of the water column. Atmospheric $CO_2$ dissolved in open ocean systems is enriched in $^{13}C$ relative to $CO_2$ derived from aerobic or anaerobic degradation or organic matter. During the latest Cenomanian an influx of open-ocean waters enriched the euphotic zone with atmospherically derived $CO_2$, which enriched the phytoplankton and subsequently formed kerogens in $^{13}C^3$. As this influx waned in the earliest Turonian, the organically derived $CO_2$ from decaying organic matter in the underlying sediments resumed its dominance in the euphotic zone, which resulted in phytoplankton and subsequent kerogens depleted in $^{13}C$. Therefore, the isotopic changes in this Cenomanian-Turonian section cannot be attributed to changes in the type of organic kerogen, which show wide variations in delta $^{13}C$ values.

Second- and third-order cycles and smaller-scale, climatic cycles of 40 and 100 Ka year durations can be calibrated by means of graphic correlation. This technique provides an independent method of measuring the durations of the marl-limestone cycles in the Greenhorn and Fort Hays units. At the Cenomanian contact a dramatic increase in sediment accumulation is recorded. During the late Cenomanian cycles were about 168 Ka years long; and during the early Turonian cycles were about 44 Ka years long. In the Fort Hays Hattin's cyclic beds represent about 113 Ka year periodicity. These figures are approximate and based on uncompacted thicknesses. Graphic correlation is a useful technique for separating short-term climatic cycles from long-term tectono-eustatic cycles.

# MARINE SHALES OF ALBIAN TO TURONIAN COLORADO GROUP, WESTERN CANADA: SEDIMENTOLOGY, GEOCHEMISTRY AND PALEONTOLOGY —PRELIMINARY RESULTS

BLOCH, J.[1], D.A. LECKIE[1], J. Wall[1], C. Schroeder-Adams[2], C. Singh[3], and M. Wilson[4]
[1]Institute of Sedimentary and Petroleum Geology, Geological Survey of Canada, 3303-33rd St., NW., Calgary, Alberta T2L 2A7 CANADA
[2]Schroeder Paleoconsulting, 5828 Dalcastle Crescent, NW, Calgary, Alberta, T3A 1S4 CANADA
[3]Alberta Geological Survey, Alberta Research Council, P.O. Box 8330, Postal Station F., Edmonton, Alberta, T6H 5X2 CANADA
[4]Department of Zoology, University of Alberta, Edmonton, Alberta T6G 2E9 CANADA

The Colorado Group of the western Canadian foreland basin, in part from the top of the Viking Formation up to the Second White Speckled Shale (SWS; Albian to Turonian), comprises dominantly mudstone and siltstone with intercalated sandstones. Massive, graded, and reworked bentonites, <1 to 25-cm thick, are common. The interval forms an eastward-tapering wedge, thinning from >800 m in western Alberta to <100 m in Manitoba.

Sedimentological, geochemical and paleontological aspects of these rocks are highly complex, showing considerable lateral and vertical variability. Regional isopachs indicate subtly shifting depocentres. A previously unrecognized drop in relative sea level near the top of the Albian is indicated by a thin, regional conglomerate marker. Sand bodies that occur between the Viking Fm. and the Fish Scales Zone (FSZ), including the Barons and St. Walburg sandstones, are thin (<10 m), contain abundant green marine clays and may be intensely bioturbated, suggesting shelfal deposition. The Dunvegan Fm. represents a thick deltaic succession occurring between FSZ and SWS in NW Alberta and NE British Columbia. Persistent, thin (1–15 m) siltstone to medium-grained sandstone units occur within the same interval across Alberta and Saskatchewan suggesting a relative lowering of sea level.

The FSZ (Albian/Cenomanian contact) contains abundant fish remains, has a very low dinoflagellate diversity and little or no bioturbation. The fish debris are exclusively disarticulated and for the most part comprise scales, superficial skull bones and vertebrae. The disarticulated occurrence and concentration of fish remains are consistent with a nearly continuous rain of fish debris onto the sea floor over a long interval of time with a reduced clastic-sediment input. Bone beds occur within the FSZ suggesting concentration of fish debris by storm or current activity. This interval is often barren of foraminifera or yields a low-diversity agglutinated assemblage. This assemblage increases in total numbers and species in the underlying Late Albian sediments. TOC values vary from 1 to 7.5 wt.%. HI and OI values suggest that the organic matter is a mixture of Types II and III. Sulphur content ranges from <1.0 to about 2.5 wt.%.

The SWS (Cenomanian/Turonian contact) is calcareous, containing sand-sized concentrations of rhabdoliths, coccoliths and large *Inoceramus* shells. The foraminiferal assemblage of the lower SWS in eastern Alberta is characterized by a poorly developed, low-diversity agglutinated fauna. Terrestrial organic matter is present suggesting a shallow-water environment. A transgression in the upper part of SWS is indicated by a high number of planktonic foraminifera, low in diversty. TOC values in the SWS range between 4–5 wt.% and organic matter is typically Type II (high HI and low OI). Sulphur content ranges from <2 to 4.4 wt.%. There is sparse to no bioturbation.

The SWS and FSZ are regional wireline log markers that indicate elevated gamma-ray fluxes. In addition to their organic-matter content and composition, these characteristics suggest that the SWS and FSZ are condensed sections. A third, shallow-water condensed section occurs at or near the base of the Colorado Group above the Viking Formation. The three condensed sections are tenatitively interpreted to represent hemipelagic sedimentation in an anoxic environment under a stratified water column. Other mudstones and siltstones are progradiational in origin, downlapping onto the condensed sections. These units typically have 1–2 wt.% TOC and Type III organic matter. Siderite concretions are common below FSZ, may occur between FSZ and SWS, but do not occur in SWS.

# SEQUENCE STRATIGRAPHY OF THE ALBIAN-SANTONIAN OF COLORADO AND WYOMING

**BOWMAN, S.A. and P.R. VAIL**
Dept. of Geology & Geophysics, Rice University, Houston, TX 77005 USA

A sequence stratigraphic analysis of Albian through Santonian strata of the Western Interior Seaway of North America demonstrates correlation with globally observed cycles. The study area includes three cross-sections which connect high resolution biostratigraphy at Pueblo, Colorado, with the thick foreland basin sediments of western Wyoming. The first N-S section is parallel to the Front Range along 64°W in Colorado and Wyoming from 20°S 24°N and was done in conjunction with Robert Weimer at the Colorado School of Mines. The second E-W section is parallel to 11°N in Colorado from 68°W to 48°W and was also done in conjunction with Bob Weimer at the Colorado School of Mines. A third E-W section is parallel to 21°N in Wyoming from 64°W to 116°W.

These sections were chosen in order to correlate relatively clastic-free marine sections of the Western Interior Seaway in Colorado with the tectonically active marine and non-marine clast-rich sections of western Wyoming, proximal to the thrust belt. The section includes three core or outcrop sections including: 1) outcrop sections at Pueblo, Colorado; 2) cored intervals of the Berthoud State #3 and #4 wells, near Fort Collins; and 3) outcrop sections at Cumberland Gap section in Western Wyoming.

Sequences and system tracts have been correlated with ongoing research on globally observed third-order cycles. Most of the globally observed cycles are represented and two new cycles are documented. Well logs containing spontaneous potential, resistivity, and gamma ray measurements offer an excellent database on which to correlate cycles with 0.5–1.0 Ma duration with thicknesses ranging from 50–100 feet. "Milankovitch" scale cycles can be correlated within many of the systems tracts, especially within the intervals containing the Lincoln and Niobrara Limestone.

A subsidence analysis shows a strong correlation between Transgressive-Regressive Facies cycles and the subsidence history of the basin. Two subsidence events are observed lasting from 98–90 Ma, and 90–80 Ma. The subsidence events are bounded by periods of stability at 98, 90 and 80 Ma.

# SEQUENCES IN CRETACEOUS STRATA OF NORTHWEST CANADA: TECTONIC OR EUSTATIC?

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T2L 2A7

Eight large-scale transgressive-regressive clastic sequences have been recognized in Cretaceous strata of northwest Canada, each bounded by unconformities at the basin margins and by transgressive surfaces where the strata are unconformable. The duration of a given sequence is highly variable, ranging from about 5 my to 18 my.

The Cretaceous tectonic history of the area represents an interplay of rift tectonics related to the opening of the Canada Basin and compressional tectonics directed from the Cordilleran orogen. Rifting dominated during the Berriasian to early Aptian, but in the late Aptian and Albian compressional events began to override rifting. Since the Cenomanian, compression deformation has dominated tectonism in northwest Canada. These events have played an important role in the formation of the recognized sequences.

Major rifting events are recognized at the Berriasian-Valanginian boundary, in the late Hauterivian and at the end of the Albian, during which major erosional unconformities developed. The latter unconformity also is recognized as a breakup unconformity along the Canadian Beaufort Sea continental margin. A late Maestrichtian unconformity is associated with a major northward shift in the loci of sedimentation, interpreted to represent a major tectonic event in the Cordilleran orogen. Three of the other unconformities (early Berrisian; approximately the Valanginian-Hauterivian boundary; Coniacian-early Santonian) are more passive events, apparently not associated with any major recognizable tectonic activity.

The late Aptian to Albian sequence represents an interesting example of the possible interaction of eustatic and tectonic events. Late Aptian to early Albian time is recognized as a period of extensive inundation of western North America, an event well recorded in parts of northwest Canada where late Aptian/early Albian strata onlap the craton. This event has been attributed to a major eustatic sea-level rise by many investigators. However, in the northern Yukon there is at least 5000 m of late Aptian to Albian sediment gravity-flow deposits, deposited during this type of regional transgression. These are explained as tectonically derived sediments from the actively deforming ancestral Brooks Range to the west. This example serves as a warning that not all submarine-fan deposits are the result of major periods of sea-level lowstand.

At least five of the eight sequences are associated with active tectonism, the other three are less readily related to tectonic events. However, northwest Canada was a very tectonically active area during the Cretaceous and differentiating between eustatically and tectonically formed unconformities is not readily accomplished.

# SEQUENCE STRATIGRAPHY IN OPEN-MARGIN DEEP-WATER CARBONATES (MESOZOIC, FRENCH ALPS), COMPARISON WITH SILLED BASINS

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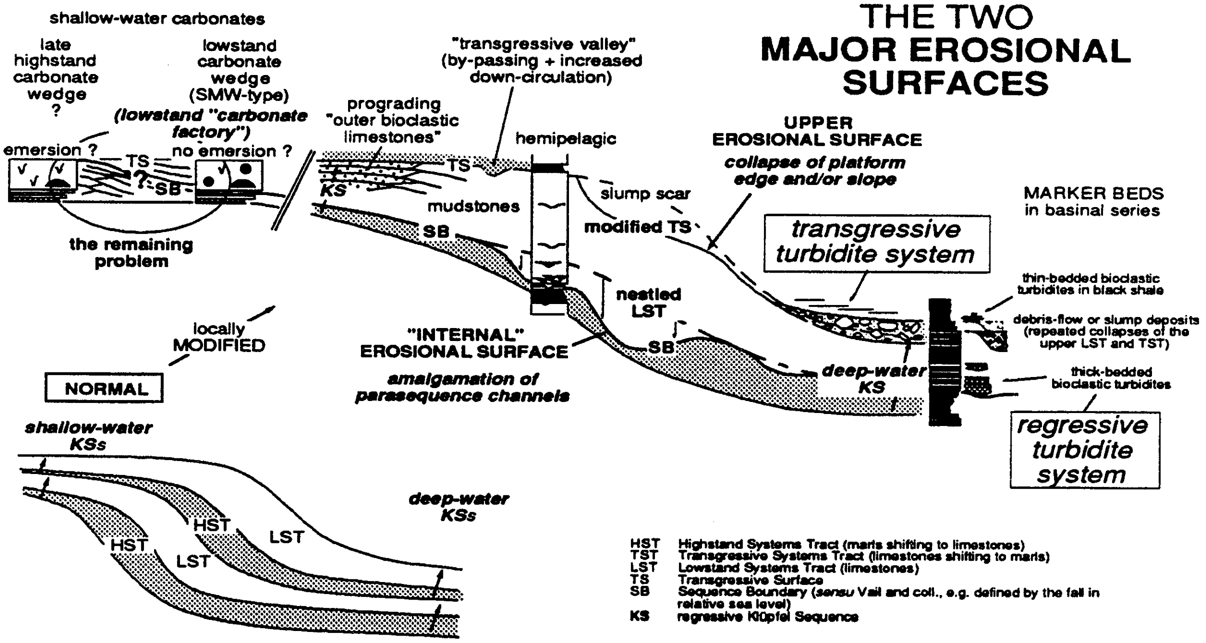
The basic fact in the Mesozoic carbonate wedge of the french alpine margin is the *pervasiveness of the regressive Klüpfel sequence across the whole depositional system,* carbonate platforms and Vocontian Trough included (see Figure). Several lines of evidences indicate that slope (hemipelagic) and basinal (subpelagic) limestones represent the lowstand tract of third order sequences, if using the new terminology of sequence stratigraphy. The remaining problem is to know where the sequence boundary goes upslope (see Figure), e.g. to interpret shallow-water carbonates in terms of relative sea level. Contrarily to what is widely accepted, most of the shallow-water carbonate progradation could represent the lowstand tract rather than the prograding late highstand wedge.

Other lines of evidences indicate that the marl shift representing the transgressive and highstand tracts in deep-water deposits is due to both a deteriorating climate that causes a fall in planktonic carbonate production, as well as due to the flooding of carbonate platforms that reduces the periplatform ooze supply. This indicates an outphasing of sea-level falls and climate coolings at the third order level of cyclicity, which should prevent from applying to third order sequences what is known to occur in the Milankovitch frequency band in the Quaternary, where climate is the very cause of sea-level oscillations. The occurrence of most parasequential slope channels in the lower part of the Klüpfel sequence is explained by the amplification of the climate-controlled, high-frequency, sea-level oscillations during the third order sea-level highstand. It is the third-order **tectono-eustatic (? pulses in global mantel activity) modulation of the orbital signal.**

The other major contribution is that two erosional surfaces, sealed by different kinds of gravity deposits, have been evidenced in the carbonate wedge (see Figure). Comparisons with deltaic systems, where the key-feature, the Klüpfel sequence, cannot be traced in deep-water clays, suggest that the erosional surface that ends many deltaic progradational phases may be equivalent to the modified transgressive surface of carbonate systems. If correct, as already suggested by Galloway (1989), many ancient turbidite systems, especially those rooted in deltaic sequences could be transgressive deposits rather than being lowstand fans.

So, considering the deep-water (or relatively deep-water) carbonate depositional sequence only, the general rule in the Mesozoic Vocontian Trough is that a more limy sedimentation represents sea-level lowstands, and marl shifts evidence sea level rises. This rule remains true in distal, fully pelagic basins of the Tethys, but lower accumulation rates do not allow the signal to be recorded in most cases with as much accuracy than in that proximal Trough. Comparison with the U.S. Interior Seaway shows that carbonate maxima there are associated with sea level rises, whereas lowstands are related to an overall shaly deposition and fast deltaic progradation. The same may also be encountered in some North African or North European basins. In summary, the deep-water carbonates behave the opposite way in semi-restricted basins and in fully open environments versus sea level changes.



*Study supported by a French CNRS-INSU grant "Dynamique et bilans de la Terre, Message sédimentaire"*

# SEQUENCE STRATIGRAPHY, LOWER CRETACEOUS, FALL RIVER SANDSTONE, NORTHERN POWDER RIVER BASIN, WYOMING AND MONTANA

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Complex associations of interbedded sandstones, siltstones and shales make up the Lower Cretaceous (Albian) Fall River Formation in a 50 by 96-mile area of the northeastern Powder River Basin and adjacent Black Hills. Seven lithofacies are recognized in core and outcrop. Lateral and vertical facies relationships, determined from wireline logs, cores and outcrops, document three episodes of shoreline progradation. Each of these parasequences is bounded above and below by a marine flooding surface. A typical cycle in outcrop contains from bottom to top: (1) marine shale and siltstone; (2) marginal marine (foreshore and shoreface/delta front) siltstone and sandstone; (3) coastal plain deposits, including distributary channel (mouth-bar), crevasse splay and marsh deposits, and (4) destructional (shoreface) sandstones, overlain by marine siltstones and shales or paleosol horizons. An individual parasequence is recognized in the subsurface on the basis of funnel-shaped gamma ray log patterns with an average thickness of 40 feet. Together the three parasequences form a retrogradational series of sandstone tongues that project into the basin from southeast to northwest.

Sequence bounding unconformities occur between the lower and middle and the middle and upper parasequences. Evidence for the lower sequence bounding unconformity is restricted to the subsurface in the northern portion of the study area. Linear sandstone bodies, interpreted as incised valley fills, have a maximum thickness of 75 feet, a width of 10 miles and are oriented northwest-southeast perpendicular to the inferred shoreline. Gamma ray logs in these sandstone bodies display cylindrical to bell-shaped patterns. Evidence for the upper sequence bounding unconformity is found in outcrops in the Black Hills and in the subsurface. In outcrop marginal marine facies of the middle parasequence are locally incised and replaced by thick trough to planar cross-bedded sandstones and bioturbated mudstones of fluvial and estuarine origin. In the subsurface contemporaneous incised valley deposits, recognized on the basis of cylindrical to bell-shaped log patterns, form northeast-oriented belts with a maximum thickness of 65 feet and widths that range from less than one mile in the south to 10 miles at the northern limit of the study area.

# THE EFFECTS OF TRANSGRESSIVE/REGRESSIVE FACIES CYCLES ON THE STRATAL PATTERN OF SYSTEMS TRACTS: THE BARREMIAN-APTIAN PLATFORM-BASIN TRANSITION IN THE VERCORS (NORTHERN SUB-ALPINE CHAINS, FRANCE)

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At the scale of seismic sections, the Barremian-Aptian platform-basin transition in the southern Vercors (France) provides a good example of carbonate sedimentary response to relative sea-level changes.

From the stratal patterns displayed in outcrop, we determined that carbonate lowstand systems tracts are major components in the basin, even in the deep response to starvation. In contrast on the shelf, transgressive and highstand systems tracts are the major components. Carbonate lowstand and shelf margin systems tracts pinch out in the vicinity of the offlap break.

From the lower Hauterivian up to the upper Aptian time, we determined seventeen depositional sequences. For purpose of identification, they are labelled H1 to H7 for the Hauterivian, B1 to B5 for the Barremian and A1 to A5 for the Aptian. On the basis of stratal patterns and systems tracts thicknesses, they are arranged into two major systems.

The first ten sequences (lower Hauterivian-lower Barremian in age) occurred during a period of overall regression. During the Hauterivian, they led to the gradual filling of the former late Jurassic by-pass margin and a large distally steepened hemipelagic ramp developed. Close to the Hauterivian/Barremian boundary, a major drop of the relative sea level emerged the inner domain of the platform. It was followed by a downward shift of the carbonate factories, now located along a narrow belt around the previous emerged platform, onto the hemipelagic ramp. The next sequences are characterized by the deposition of very thick lowstand systems tracts in the basin and by thin transgressive and highstand systems tracts on the platform. The tops of the lowstand systems tracts represented the maximum progradation of bioclastic facies into the basin for each sequence, a response caused by the decreasing rate of generation of accomodation space produced by low rates of tectonic subsidence.

The seven last sequences (upper Barremian-Aptian in age) relate to a transgressive phase, during which the Jura platform was gradually drowned. They evolve from overall aggradation to overall retrogradation. During the early transgressive phase the TST and HST are thick and widespread on the platform. Shelf margin systems tracts are dominant over lowstand prograding complex. These thick shelf sequences indicate that there was accomodation space on the platform for sedimentation and that the carbonates were able to keep up and fill the space. At the end of the early Aptian, the carbonate platform is drowned and overlaid by condensed deposits. They form the late transgressive phase. Thick black shales are present in the basin in the same time. This is a product of a more and more transgressive context resulting from the super-imposed effects of high rates of tectonic subsidence and of long-term rise of the eustatic sea level. These condensed sequences indicate accomodation space was being created of a greater rate than the carbonates could fill causing them to "give up".

# VARIATIONS IN ALLUVIAL ARCHITECTURE IN A TRANSGRESSIVE SYSTEMS TRACT, DAKOTA FORMATION, UTAH

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The nonmarine strata of the Dakota Formation in Utah were deposited during a eustatic rise in sea level and are part of a transgressive systems tract. This systems tract was investigated in two regions, the Kaiparowits Plateau of southern Utah and the San Rafael Swell of central Utah. In both areas, the Dakota overlies a regional unconformity and is overlain by marine shales of Cenomanian age. The shales contain bentonites that downlap a surface located a few meters above the alluvial deposits. Deposits of the two areas have contrasting styles of alluvial architecture and have different amounts of associated coal deposits.

In the Kaiparowits Plateau, the alluvial Dakota is from 2 to 300 m thick. Differential subsidence in the foreland basin resulted in a thicker section towards the western thrust belt. Four widespread coal zones separate clastic units that are up to 20 m thick. These zones contain carbonaceous, fossiliferous, and rooted mudrock, thin-rippled sandstone, and coal, which are thought to have accumulated in mires containing minor lakes and low-energy fluvial channels. Coal beds are up to 1.5 m thick in the study area but reach 5.5 m farther west. Intervening clastic units consist of laminated mudrock, rippled sandstone sheets, and cross-bedded ribbon bodies. Rippled sandstone and mudrock represent crevasse-spaly and overbank deposits. Ribbon sandstones are 1–9 m thick and 15–160 m wide, have lateral accretion surfaces, and were deposited by slightly sinuous streams. Within the clastic units, numerous coeval channels, of various sizes, suggest an anastomosed system of channels that resulted from the diversion of major river systems into the mire environment.

In the San Rafael Swell, the alluvial deposits of the Dakota Formation are 0–40 m thick. A lower unit of interconnected crossbedded sandstones is traceable along depositional dip for about 50 km. These amalgamated channels are valley-fill deposits. Few overbank deposits are preserved because the confined channels continually reworked finer sediment. An upper unit has rippled sandstones, mudrock and a few thin discontinuous coal beds. The rippled sandstones are 2–3 m thick, highly sinuous, and ribbonlike. These facies represent deposits of small meandering rivers and associated mires on a low-gradient coastal plain. They grade upward into burrowed and oyster-bearing sandstones and shales, indicating evolution into tidal and lagoonal environments.

The contrasting facies architecture in the two regions may be related to relative rates of base-level rise. Both sequences accumulated during the same eustatic rise in sea level, but subsidence rates were different. In the San Rafael Swell, the amalgamated channels accumulated during a slow rise in base level, whereas the lenticular coals and enclosed channels of the upper unit reflect a gradual increase in the rate of base-level rise. In the Kaiparowits, the greater thickness of section and larger amount of coal are due to the faster rate of base-level rise resulting from subsidence.

# THE EFFECTS OF MIDDLE TO LATE ALBIAN SEA-LEVEL FLUCTUATIONS IN THE PEACE RIVER FORMATION OF WESTERN CANADA: INCISED VALLEYS, PALEOSOLS, ESTUARIES AND SHALLOW-WATER CONDENSED SECTIONS

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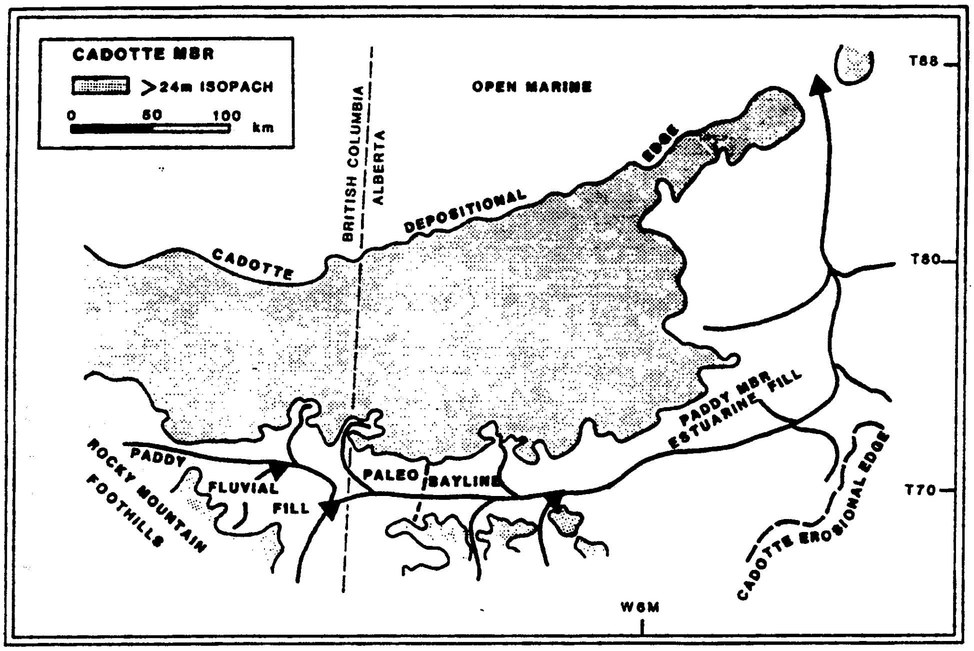
The Middle to Late Albian stage in western Canada is fraught with multiple unconformities varying from short diastems represented by paleosols to angular unconformities with multi-million year gaps. The unconformities are directly attributable to changes in relative sea level. The Middle to Late Albian Harmon, Paddy and Cadotte mbrs (Peace River Fm) were deposited during an interval of fluctuating sea level which roughly corresponds to the 97 my sea fall. The Cadotte Mbr, deposited during a sea-level highstand, prograded northwards during a forced regression as a wave-dominated shoreline which extended eastwards for more than 300 km. Subsequent sea-level fall resulted in incisement into Cadotte sediments, of an east-west valley system which was more than 300 km long, 70 km wide, and 15–20 m deep. Second and third order drainage networks are recognizable. Basal lowstand fluvial deposits are present at the axes of the incised valleys, expressed as narrow-deep, axial channel deposits. The overlying Paddy Mbr was deposited during subsequent sea-level rise, during which time the incised valley became infilled with fluvial deposits in the west and estuarine deposits in the east. The incised channels and related fill are correlative with thick paleosol development on the associated interfluves. Some of the individual paleosols may represent diastems of up to 10,000 years. Elsewhere, there are eight foraminiferal subzones missing between the Paddy and the Cadotte mbrs, possibly representing a gap of a few million years. With continued sea-level rise, the drowned river valley became a broad, tidally-influenced embayment bounded on the north by a large barrier system. Marine transgression of the Paddy Mbr is represented by ravinement surface. Isolated sandbodies at the top of the Paddy Mbr are inferred to be tidal-inlet deposits formed during transgression and shoreface erosion. The lower most Shaftesbury Fm, a marine, organic-rich, radioactive shale, directly overlying the Paddy Mbr represents a shallow-water condensed section, characterized by high carbon contents, abundant preserved algae cysts, evidence of anoxia and high gamma-ray counts. The Peace River Arch played a major role in the deposition and preservation of sediments of the Peace River Fm.



Isopach of the Cadotte Mbr. Values less than 24 m (white) represent an east-west trending valley system incised into the Caddote Mbr during lowstand. Subsequent Paddy Mbr fill was estuarine/bay fill in the east and fluvial in the west. The regional map is baded on 4700 wells.

# HEIRARCHICAL AND RETROGRADATIONAL, LOWSTAND-SHELF SANDSTONES BELOW CONDENSED SECTION IN THE LOWER KASKAPAU FORMATION (UPPER CENOMANIAN-LOWEST TURONIAN), ALBERTA, CANADA

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The marine Kaskapau Formation in northwestern Alberta overlies the deltaic Dunvegan Formation and contains the earliest Turonian Second White Speckled Shale. Sedimentary structures, microfauna, megafauna and trace fossils within sandbodies of the Doe Creek, Pouce Coupe, and Howard Creek members of the Lower Kaskapau Formation indicate deposition on a shallow-marine shelf with normal to near-normal salinity. The retrogradational sandbodies are 5-7 m thick, up to 37 km long and up to 6 km wide, and encased in marine shale. These sandstone members represent a series of linear, shallow-marine sandstones deposited subparallel to the Dunvegan shoreline during brief episodes of progradation within an overall transgressive phase. Each member, as well as thinner sandbodies within individual members, is bounded by unconformities. The lower bounding surface of each sandbody represents rapid deltaic progradation during a drop in relative sea level. The leading edge of the transgression is not marked by an erosional sandstone. Rather, a thin, finely-interbedded sandstone, siltstone and shale containing a stressed trace fossil and microfaunal suite, and synaeresis cracks was deposited in a stressed environment created by deltaic, fresh-water influx during progradation. The upper bounding surface of each sandstone and of the members, transgressed and abandoned as sea level subsequently rose, is a flooding surface, sharply overlain by marine shales having outer shelf trace fossil and microfaunal affinities.

The peak of marine transgression is represented by the Second White Speckled Shale, a condensed section deposited above the Howard Creek Member. The Second White Speckled Shale contains >11% TOC, HI to 460 mg HC/g of TOC and Type II organic matter. In contrast, the other shale of the lower Kaskapau Formation averages 1% TOC, a HI of 46 mg HC/g of TOC, and contains Type III organic matter.

A heirarchy of sea level flutuations can be identified:

1. The major flooding of the Kaskapau shales coincides with a period of Late Cenomanian global sea level rise with the maximum of marine transgression as the Second White Speckled Shale occurring near the Cenomanian-Turonian boundary.

2. Minor lowstands and subsequent flooding resulted in deposition of the unconformity bounded units comprising the Doe Creek Pouce Coupe and Howard Creek members.

3. Even higher-frequency sea level oscillations resulted in deposition of individual sandbodies within the individual members. The overlapping I, N and A sandstones of the Doe Creek Member suggest high-frequency, fluctuating sea-levels and an oscillatory shoreline during an overall retrogradational interval.

The sea level changes for 2 and 3 need not be eustatic, but may be relative in nature, possibly due to autocyclic processes such as delta switching.

# STRATIGRAPHIC SEQUENCES IN THE VIKING FORMATION SOUTH-CENTRAL ALBERTA, CANADA

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The middle to Late Albian Viking Formation has previously been interpreted as comprising a single clastic wedge that prograded basinward in response to orogenic activity to the west. Utilizing facies analysis of well cores combined with sequence stratigraphic concepts, it can be demonstrated that the Viking consists of two principal stratigraphic sequences separated by a major unconformity. Weimer (1984, 1988) recognized the occurrence of a major unconformity in equivalent strata of the Viking Formation (J. Sandstone) in the Denver Basin, and suggested this depositional break could reflect a major worldwide lowstand of sea level which occurred some 97 m.y. ago. It is proposed that the major unconformity recognized in the Viking in South-Central Alberta is equivalent to the J. Sandstone unconformity in the Denver Basin.

The two principal stratigraphic sequences that comprise the Viking Formation are a lower progradational succession (highstand deposit), and an upper transgressive succession (including incised valley fill). The highstand deposit consists of a series of stacked coarsening-upward shelf-to-shoreface units. A lowstand surface of erosion (LSE) truncates the highstand deposit, and is also marked by a superimposed ravinement surface. The transgressive surface of erosion (TSE) delineates the base of the upper succession which records transgressive depositional conditions punctuated by stillstand intervals. In the distal or central part of the basin, lowstand and transgressive deposits consist of thin interbedded units of interlayered mudstone-sandstone, mudstone and granular sandstone-conglomerate. Near the western margin of the basin, antecedent linear valleys are filled with thick estuarine sediments deposited during the transgression.

# RELATIVE IMPORTANCE OF FLUCTUATIONS IN SEA LEVEL AND SEDIMENT SUPPLY IN THE ORIGIN OF MID-CRETACEOUS CLASTIC WEDGES, CENTRAL ROCKY MOUNTAIN REGION

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Clastic wedges and the transgressive-regressive shoreline movements that they record are primarily the result of: 1) changes in relative sea level, 2) varying rates of delivery of sediment from the orogenic belt to the basin margin, or 3) a combination of these two. Accordingly, clastic wedges may theoretically be characterized as: 1) eustatic, 2) tectonic, or 3) hybrid type. Speculations regarding the origin of a particular clastic wedge can be made on the basis of its areal distribution and thickness, contained rock types, and the nature of any associated unconformities.

Sea level is a relatively simple term, combining eustacy and broad patterns of basinal subsidence or uplift. Sediment supply is a more complicated term. For purposes of analyzing the origins of clastic wedges in foreland basins, the most important factor relative to sediment supply is not how much sediment is created by erosion in the thrust belt, but rather how much is passed across the foredeep and contributed to coast-plain and shallow-marine environments.

The Cretaceous basin of the Rocky Mountain region includes examples of all three types of clastic wedges. The late Albian clastic wedge that comprises the Dakota, Bear River, and Muddy formations in Wyoming is a eustatic-type wedge. It is thin and widely distributed. It lacks coarse sediment in all but its westernmost part and contains two or more widespread unconformities, at least one of which is of subaerial origin. The Cenomanian-Turonian clastic wedge represented by the Chalk Creek-Belle Fourche part of the Frontier Formation in Wyoming is a tectonic-type wedge. It is areally restricted and thick, includes substantial amounts of coarse sediment, and lacks significant unconformities formed contemporaneously with deposition. The Turonian-Coniacian clastic wedge that comprises the Oyster Ridge and Dry Hollow Members of the Frontier in Wyoming and Utah and the Ferron Sandstone Member in Utah is a hybrid-type wedge. It combines the important characteristics of the other two types.

# SEQUENCE STRATIGRAPHY OF THE CRETACEOUS

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Areas of studies:

(1) Sub-Alpine Basin (France) *Berriasian-Cenomanian*
(2) North Sea and Paris Basin *Cretaceous*
(3) Western Interior Basin, Colorado, Wyoming *Late Albian-Campanian*
(4) Gulf of Mexico Basin, U.S. and NE Mexico *Cretaceous*
(5) Neuquen Basin (Argentina) *Berriasian-Barremian*
(6) Exmouth Plateau, Otway and Gippsland Basin (Australia) *Barremain-Maestrichtian*

Purpose:

(1) Identify Transgressive/Regressive Facies Cycles (Second Order Cycles) and Sequences and Systems Tracts (Third Order Cycles) which are the building blocks of the Second Order Cycles.

(2) Relate Transgressive/Regressive Facies Cycles to the combination of the tectonic subsidence pattern and the changes in the long-term sea level pattern.

(3) Relate Sequences and Systems Tracts to short-term sea level changes within the accommodation space created by the subsidence.

Example: Sub-Alpine Basin in France

The early Cretaceous platforms surrounding the sub-Alpine Basin in France display two Transgressive/Regressive Facies Cycles.

The first Transgressive/Regressive Facies Cycle has a duration of about 13 M years from the middle Berriasian to the middle Barremian. It is made up of 17 depositional sequences (labeled Be4 & Be5 for the upper Berriasian, V1 to V6 for the Vallanginian, H1 to H7 for the Hauterivian, B1 & B2 for the lower Barremian). The transgression peak is reached in the basal part of the Hauterivian with the drowning of the platforms. The regressive phase is characterized by the progradation of bioclastic facies onto the flooded platforms and even basinward in the latest stage of the regression. This regression is a response to the decreasing rate of generation of accommodation space due to low rates of tectonic subsidence.

The second Transgressive/Regressive Facies Cycle has a duration of about 17 M years from the upper Barremian to the upper Albian. It is made up of 13 depositional sequences (labeled B3 to B5 for the upper Barremian, A1 to A5 for the Aptian, A11 to A15 for the Albian). We relate the onset of the transgressive phase with the change from overall progradation to overall aggradation which is visible in the evolution of the Barremian platforms of the northern Sub-Alpine chains. At the end of the early Aptian, the carbonate platforms are drowned and overlain by condensed deposits, which form the late transgressive phase. Thick black shales are present in the basin in the same time. They are a product of more and more transgressive setting resulting from the super-imposed effects of high rates of tectonic subsidence and long-term rise of eustatic sea level. The regressive phase during the Albian is indicated by terrigenous input on the flooded platforms and in the basin. They occur without a real decrease of the tectonic subsidence.

# WESTERN INTERIOR CRETACEOUS PROJECT (WIK) AND SEQUENCE STRATIGRAPHY

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The Western Interior Cretaceous Project (WIK) is a part of the Cretaceous Resources, Events and Rhythms Project (CRER) of the Global Sedimentary Geology Program (GSGP). Nearly 100 scientists, organized as WIK, are compiling and interpreting surface and subsurface reference sections in the Western Interior to increase understanding of basinwide sedimentary products and the processes that controlled their formation. One goal of WIK is to have a publicly available computer data base from which to reconstruct the depositional history of the Western Interior Basin, and to establish global processes and events by comparison with other basins in the world. Concepts of sequence stratigraphy and sea level changes are being tested as a part of the efforts of Working Group I of CRER.

Preliminary analysis indicates difficulty in applying to the Western Interior Basin many of the sequence stratigraphic concepts and terms established from the sedimentary record of the passive margins of continents (Exxon Model). A partial list of problems includes: 1) usefulness and validity of sequence stratigraphic terminology in relation to terminology as defined by the North American Stratigraphic Code and applied in traditional sedimentary geology investigations; 2) tracing sequence boundaries basinwide from areas of subaerial exposure (unconformities) to conformable sections, or vice versa; 3) establishing sequences, and their subdivisions, as lithostratigraphic or chronostatigraphic units; 4) determining water depths and depositional or structural topography in relation to types and rates of sedimentation during relative sea level changes; 5) influence of basement-controlled fault systems on intrabasin unconformities and sedimentary patterns; and 6) determining if relative sea level changes result from tectonic movement or eustacy, or a combination of both.

The lower Cretaceous of the Western Interior is described as a case history to illustrate the use and modification of sequence stratigraphic concepts and their application in petroleum exploration.

# *Cyclostratigraphy*

# GEOCHEMICAL EXPRESSION OF MILANKOVITCH CYCLES IN CRETACEOUS PELAGIC MARINE STRATA OF THE WESTERN INTERIOR SEAWAY

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The Cretaceous Western Interior Sea as a northwestern arm of the Tethys sea apparently was extremely sensitive to orbital forcing during transgressive episodes, resulting in long cyclic sequences of complex origin. Two carbonate sequences, the Niobrara and Greenhorn Formations, were deposited during the maximum transgressive episodes. Inorganic and organic geochemical investigations across decimeter-scale bedding cycles in pelagic carbonate sequences of the Greenhorn and Niobrara Formations provide a basis for understanding the complex origins of the limestone-marlstone cycles. In these strata, the cycles are manifested in variations in color (dark/light), carbonate and organic-carbon content, concentrations of trace and major elements, and sedimentary structures. On the basis of a detailed study of the Niobrara Formation, we recognize a hierarchy of cycles with average periodicities of about 20 ky, 100 ky, 280 ky, and 1.7 Ma. The Bridge Creek Limestone Member of the Greenhorn Formation exhibits small-scale cyclicity with estimated subtle 20-ky cycles bundled into stronger 100-ky cycles. The cycles in both units are well-defined by variations in carbonate and organic carbon. In addition, inorganic geochemical variations indicate changes in the composition of the detrital-clastic component across each cycle; systematic variations in Si/Al, Ti/Al, Mg/Al, and Na/K ratios, for example, suggest that the cycles are, in part, due to variable dilution by terrigenous clastic material delivered from the Sevier highlands to the west of the seaway. The limestone beds are characterized mainly by a geochemical signature of altered volcanic ash, whereas the geochemistry of the marlstone beds more strongly reflect the detrital-clastic component. In addition to dilution, the Niobrara cycles are also partly the result of varying carbonate productivity, with highest productivity coinciding with periods of low detrital influx. Sr, Mn and other trace elements, and carbon and oxygen isotope variations reflect mainly the effects of differential carbonate diagenesis across the cycles. Diagenesis also has enhanced the visual expression of cyclicity by preferential carbonate cementation in the limestone beds. However, depleted $\delta^{18}O$ values in most marlstone beds of the Bridge Creek Limestone Member may indicate that influx of terrestrial detrital material was accompanied by decreased surface-water salinities as the result of substantial freshwater runoff to the basin.

Other elemental (transition metals; sulfur) and organic geochemical (organic carbon, pyrolysis, $\delta^{13}C$) variations across the cycles reflect redox variations that also accentuated the cyclicity. Preservation of marine organic matter was enhanced during the increased runoff hemicycle, possibly as the result of increased water-mass stratification and benthic oxygen depletion.

# TIME MEASUREMENT AND CORRELATIONS BY HIGH-FREQUENCY SEDIMENTARY CYCLES: LIMITS OF METHODS

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As Earth Sciences need more and more accurate time measurements, sedimentary cycles, recording periodic geodynamic controls of various origins, are frequently used as geochronometers.

Very high-frequency cycles have short periods ranging from half a day (tidal cycles) to one year (varves). In conditions of optimum preservation (little or no alteration by currents, bioturbation and compaction) and of high sedimentation rate (e.g. lacustrine deposits, evaporites) varves allow to count time intervals up to 250 Ky, to evidence Milankovitch periods and to correlate sections over distances exceeding 100 km. These tools are unsuitable because overaccurate with regard to the length of many geodynamic processes; they are useful to quantify short time intervals in exceptional sedimentary and environmental conditions.

High-frequency cycles allow measurements ranging from a few thousand to 1–2 million years. They are principally represented by bed-scaled marl/ limestone couplets settled in pelagic environments where autocyclic processes are damped. Dependent on global climatic events, these cycles allow very fine correlations over large areas such as the Tethys (for example from Southeastern France to the Gulf of Mexico or from Central Italy to Colorado).

Linked to the variations of several orbital parameters, they represent a composite signal whose basic periods are determined by spectral analysis. The first use of the 21 Ky period to calculate stage durations is due to Gilbert (1895); this method is reliable when series are made of homogenous facies and have nearly constant sedimentation rates between 20 and 30 mm/Ky. In addition, the influence of orbital cycles on the climate varies according to the latitude; the sedimentary record of climatic forcing may be perturbed by local processes such as tectonics, bioturbation, oceanic circulation; lastly the 21 Ky period is unsteady through Geological time.

Cycles linked to orbital periods are also recorded in epicontinental areas; such are the PACs of Goodwin and Anderson (1985), resulting from sea level fluctuations or subsidence pulses. Although synchronous at a basin-scale theoretically, this signal is often disturbed by autocyclic dynamics and its recording is discontinuous generally owing to occurent erosions during emersions.

High-frequency cycles are the most reliable and widely distributed but they cannot represent the ideal way for time measurements and correlations except when used in some strict conditions. In deep marine environments they are too dependent on sedimentation rates, in shallow areas their vertical and horizontal continuity is most often disturbed by autocyclic processes.

# PERITIDAL CYCLICITY IN THE MILANKOVITCH BAND: BARREMIAN CARBONATE DEPOSITS OF MONTE MAGGIORE (SOUTHERN APENNINES, ITALY)

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Carbonate peritidal deposits of lower-Cretaceous age, widely cropping out in the carbonate platform sequence of southern Italy, carry distinct signals of cyclicity in the Milankovitch band.

We have studied the depositional and diagenetic facies organization of a 120-m thick sequence of Barremian age, at Monte Raggeto (M. te Maggiore, near Naples) where, from a total of 60 m, two sedimentary modules have been recognized: (a) depositional cyclothems: rare, made of several subtidal-supratidal couplets and topped by a supratidal interval; (b) diagenetic cyclothems (concu D'Argenio 1975, 1976; Hardie et al., 1984), very common, made of prevailingly subtidal intervals with emersion-generated features (karst, reddened surfaces) superimposed in their upper part.

Cyclothems along the sequence tend to group into fairly regular intervals, each about 10-m thick, formed by sets of 7 to 10 units; both single cyclothems and sets suggest a high frequency cyclicity.

Fourier analysis of variable parameters (textures, sedimentary structures, emersion-modeled surfaces and recurrence and intensity of early dolomitization as well as thickness of the above features) reveals three main periodicities close to Milankovitch modulation (about 18.5 Ka, 39.7 Ka, and 122.3 Ka, assuming 2000 Ka as a reasonable length of time represented by the measured 40 m of sequence).

We propose that the observed cyclicity indicates Barremian sea-level oscillations induced by high frequency eustatic control.

# ORBITALLY DRIVEN CYCLES IN TRACE FOSSIL DISTRIBUTION FROM THE PIOBBICO CORE (LATE ALBIAN, CENTRAL ITALY)

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After a long series of investigations concerning sedimentology, micropaleontology, and geochemistry of the Aptian-Albian Scisti a Fucoidi cored near Piobbico (Marche, Italy), a detailed study of the trace fossil distribution was performed.

In order to reconstruct the bottom-water oxygenation history, the following parameters were taken into consideration: (a) absence/occurrence of bioturbations; (b) type of trace fossils (ichnogenera); (c) density of bioturbation; (d) maximum burrow diameter; (e) maximum penetration into sediments.

Distribution of trace fossil density yielded a square wave function that was subsequently smoothed using a five-point triangular filter. For Fast Fourier spectral analysis a two-meter window, moved in 50-cm steps, was used in order to attenuate distortions introduced by variations in sedimentation rate.

The stacked spectrum shows three main peaks with periodicities of 123 ka, 41 ka, and 20 ka which are evidently correlatable with the orbital parameter cycles.

Cross-correlation of trace fossil density and carbonate content curves reveals no displacement. This clearly means that the increased seasonality, leading to a better stirring of the oceans, is responsible for both the increase in carbonate primary production and the enhancement of bottom-water ventilation.

# PALEOFERTILITY MILANKOVITCH CYCLES IN CALCAREOUS NANNOFOSSIL ASSEMBLAGES: EVIDENCE FROM THE ALBIAN GAULT CLAY FORMATION

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A quantitative study of calcareous nannofloras was applied to the Albian Gault Clay Formation (England). This formation consists of grey marly claystones and claystones with phosphatic nodules and glauconitic layers as minor lithologies.

Two cores were analyzed in detail to focus changes in calcareous nannofossil composition and their significance. Samples were routinely collected every 5 cm, but sampling was even more closely spaced in proximity of lithologic variations.

Preservation of calcareous nannofossils is excellent and therefore diagenesis cannot be invoked to explain, not even partially, changes in nannofloral assemblages.

Principal Component and Factor (R-Mode) Analyses extracted two factors (with eigenvalue > 1) correlated to fertility and temperature respectively.

Fast Fourier spectral analysis was performed on percentages of selected nannofossil species. The fluctuations in abundance of both *B. constans* and *W. barnesae*, regarded as fertility and non-fertility indices respectively, resulted to be orbitally driven for spectral analysis showed periodicities of 22–26 kyr (precession cycle), 40 kyr (obliquity cycle), and 100 kyr (short eccentricity cycle).

The axial obliquity cycle is the strongest signal, as expected at high latitude (Boreal realm). At lower latitude (Tethyan realm) fertility was documented to be directly correlated with carbonate production. On the contrary, in the Gault Clay cores carbonate content could not be directly correlated to fertility, being *B. constans* and *W. barnesae* abundance out of phase in respect with $CaCO_3$ content.

Both *R. parvidentatum* and *P. asper*, cold and warm water species indicators respectively, show a weak evidence of orbitally driven fluctuations. However, once again the obliquity periodicity (40 kyr) is documented.

Milankovitch cycles are preserved in the abundance fluctuations of other taxa, such as *Zygodiscus spp*. Unfortunately, their paleoecological significance is still unknown.

# THE ORBITAL BEAT: KEY TO HIGH RESOLUTION PALEOCLIMATIC AND PALEOFLUX STUDIES IN THE CRETACEOUS

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Study of Pleistocene climates has been revolutionized by time series analysis of such variables as calcium carbonate content and oxygen isotopic values in marine sediments. Once statistical methods showed conclusively the link between oscillations in sediment climate proxies and periodic forcing of climate by changes in the earth's orbital elements, paleoceanographers had a unique tool for understanding climate change over the past few hundred thousand years. Events in the world ocean could be correlated to within a few thousand years thanks to the pervasive orbital signature in paleoclimate. This talk will present evidence that orbital climatic rhythms march back in time into Cretaceous age sediments. I will review available data drawing, in addition to my own work, on that of Arthur, Dean, DeBoer, Erba, Fischer, Napoleone, Park, Premoli Silva, Ripepe, and Schwarzacher. I will then sketch the promise that Cretaceous "cyclostratigraphy" holds for future studies of Cretaceous paleoclimate and paleoceanography.

Variations in carbonate content and sediment color on a decimeter-length scale are common in Cretaceous sediments. At least three strands of evidence are required to tie the alternations observed in Cretaceous strata to orbital forcing. Evidence that orbital cyclicity extends from the late Pleistocene into the earlier Tertiary in an unbroken fashion demonstrates that such rhythmicity is the rule in the past, and that "Milankovitch radiation forcing does not require Northern Hemispheric ice sheets for climatic expression. The second requirement is for detailed statistical analysis of Cretaceous time series. The link into orbital forcing generally comes from frequency ratio arguments, since many Cretaceous sequences are still poorly dated. Lastly, in the best circumstances, Cretaceous paleoclimatic periodicities can be dated directly. Data sets from DSDP/ODP coring, including physical property logs and digitized photographs, and outcrop and core studies in Italy will be used to develop this argument.

What can be learned from the orbital connection to Cretaceous sedimentation? We do not yet have a global picture of cyclic sedimentation for this time, but enough work has been done to show that an exciting picture of Cretaceous environmental dynamics will emerge. The best calibrated data set comes from a series of cores drilled by DSDP in the South Atlantic. Paleomagnetic dating (Chrons C28N-C33R) establishes a mean periodicity for carbonate oscillations of 23.5 ± 4.4 kyr, finally validating the existence of precessional cyclicity in the Cretaceous. The carbonate rhythms behave as a

# THE EFFECT OF PRECESSION AND OBLIQUITY ON CRETACEOUS CLIMATE AND CYCLIC SEDIMENTATION: A GCM MODELING STUDY

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Cyclic bedding in Cretaceous marine sediments is thought to be induced by cyclic shifts in the precipitation-evaporation balance over individual ocean basins and marginal seas. We report a set of 36 perpetual-season simulations using an atmospheric GCM to test the sensitivity of mid-Cretaceous climate (100 Ma) to insolation changes due to the precessional and obliquity cycles. We used mid-Cretaceous paleogeographic and paleotopographic reconstructions and zonally symmetric SST based on earlier work by Barron and Washington. Surface wetness and albedo values appropriate for grassland were prescribed over all land regions. We estimate linear sensitivity to orbital changes as a function of latitude and longitude, ,using the scatter in the simulations to estimate its uncertainty. Climate variables such as surface temperature, pressure and moisture transport suggest that the mid-Cretaceous climate system is more sensitive to precession than to obliquity in most regions, even at high latitudes. Obliquity variations affect our precession-enhanced continental monsoons. As a result, sensitivity to obliquity can be important at low, as well as high, latitudes. For instance, the low-latitude proto-South Atlantic region varies from a strong source (excess evaporation) with changes both in precession and obliquity. This variation is consistent with an alternation in marine conditions between a stagnant, stratified ocean basin with anoxic bottom water and an evaporative basin that produces bottom water that is warm, saline and oxygenated. The portion of the Tethys Ocean overlying the limestone/black-shale sequences in present-day Italy does not exhibit comparable behavior, but the reconstruction of orography and basin boundaries in this region is less known.

true chronometer of sedimentation rate across the Cretaceous-Tertiary boundary. They show a step function decrease in sedimentation rate at the boundary that is consistent with the impact hypothesis, and date the position of the K/T boundary within reversed polarity zone 29R. Such precise dating will be useful in measuring fluxes of sediment components just before and after the extinctions.

Orbital stratigraphy also sheds light on the conditions that led to oceanic anoxia in the mid-Cretaceous. Time series analysis of various sediment parameters shows that fluctuations in oxygenation in the North Atlantic and Tethyan basins were driven by a combination of eccentricity and precessional variations. Use of orbital chronometry permits the detailed reconstruction of sedimentation rates across the transitions from oxygenated to anoxic conditions. We find a consistent pattern of lower accumulation rates of biogenic components in the anoxic portions of the sequences, indicating that anoxic episodes were low productivity events. Cyclic changes in the latitude of deep-water formations are implied.

# LONG-TERM RHYTHMS IN THE MESOZOIC: TECTONICS, SEA LEVEL, OCEAN CIRCULATION, AND CLIMATE

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Analysis of Mesozoic geologic data, including episodes of global tectonism, sea-level fluctuations, stratigraphic sequence boundaries, mass extinctions, ocean "anoxic" events, and climatic changes, suggests rhythms of several tens of millions of years. The rhythms seem to be driven by waves of tectonic activity and seafloor spreading that control sea level and atmospheric carbon dioxide levels. The resulting climatic changes lead to fluctuations in ocean circulation that cause changes in productivity, bottom water formation and ocean ventilation.

Time-series analysis reveals an underlying periodicity of roughly 30-million years, but shorter cycles may also be present. The generally rhythmic nature of the Mesozoic is punctuated by relatively rapid (instantaneous?) events of global scale. Major turning points occur in the Late Permian (~245 Myr), Late Triassic (~210 Myr), Pliensbachian (~190 Myr), Late Tithonian (~140 Myr), Valanginian/Hauterivian (~130 Myr), Aptian/Albian (~110 Myr), Late Cenomanian (~91 Myr), and Late Maastrichtian (66 Myr). A similar pattern in extraterrestrial impacts suggests that the punctuations in the geologic record are impact generated. (Similar events occured in the Cenozoic, but in the context of a generally cooler climate.) These data provide evidence for a kind of "grand unified theory" of global tectonic/climatic phenomena.

Results of global carbonate/silicate biogeochemical cycle modeling indicates that tectonic forcing of the ocean/atmosphere/climate system can result in significant changes in ocean chemistry, rates and sites of burial of organic carbon and $CaCO_3$, and atmospheric composition on $10^7$ to $10^8$ year timescales, while large-body impacts can cause perturbations in the global biosphere and climate that may persist for $10^5$ to $10^6$ years. Further work in geochemical modeling and geologic reconstructions of past climate and paleoceanography from isotopic and other information combined with better dating of major events is needed to unravel the history of the Mesozoic earth system.

# RECONSTRUCTING DEPOSITIONAL GEOMETRIES AND INTERPOLATING AGE INFORMATION AT THE PARASEQUENCE SCALE

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As part of our effort to prepare stratigraphic datasets for model-data comparison, we attempted to assign geologic ages to depositional episodes between points of chronostratigraphic control. This effort required a two-step procedure: (1) restoring the data set to pre-compacted stratigraphic geometries, and (2) assigning geologic ages to depositional episode boundaries utilizing different interpolation techniques. Although originally developed to prepare data sets for model-data comparison, these techniques can also be used to evaluate the assumptions which go into interpretations of Milankovitch-type cyclicity in the rock record.

In recent years, studies of geologic sequences have gone beyond basic facies descriptions to include genetic interpretations of the major parameters affecting the overall basin-fill history. In addition to inferring depositional processes from sedimentary structures, attempts are being made to understand the relative importance of allogenic, autogenic, and/or random geologic mechanisms in imparting apparent depositional cyclicity. Depositional cyclicity on the parasequence scale occurs on the order of $10^3$ to $10^5$ years. These durations overlap between astronomically controlled forcing functions and random or chaotic geologic-process mechanisms is hindered by our inability to resolve geologic time below the $10^6$-year level. Consequently, most attempts to calculate the duration of small, parasequence-scale depositional episodes have relied upon the linear interpolation of ages between points of chronostratigraphic control on compacted stratigraphic sections.

To investigate alternative techniques for age interpolation, we analyzed and prepared two Cretaceous-aged data sets from the Western Interior Seaway of the United States: the Blackhawk Formation in East-Central Utah and the Fox Hills-Lewis Formations of the Red Desert/Washakie basins of South-Central Wyoming. Both data sets comprise siliciclastic shoreline systems which display two scales of apparent cyclicity: parasequence scale cycles on the order of thirty meters and parasequence stacks on the order of one hundred meters which are variously arranged in progradational, aggradational, and retrogradational patterns.

We first restored the stratigraphic sections to their near-surface stratigraphic thicknesses and depositional geometries, in order to remove compaction-related distortion. Given a restored cross-section we then utilized different assumptions to interpolate age information between our points of chronostratigraphic control. We applied two basic age-interpolation techniques utilizing two different operating assumptions. The first assumption is that the rate of subsidence or relative base level rise was constant through time. This assumption is equivalent to applying a linear interpolation between points of age control and implies that the two orders of depositional cyclicity resulted from variations in sediment input rate over time. The second assumption is that rates of sediment input are constant through time and implies that the depositional cyclicity results from variations in relative base level over time. Both assumptions are imperfect and represent end members in the explanation of depositional cyclicity.

The range of age assignments which result from these two different interpolation techniques highlights the range of uncertainty which exists in estimating ages and cycle periods between points of age control. A careful treatment of the estimation uncertainty should accompany any attempt to assign a Milankovitch origin to observed stratigraphic cyclicity.

# CORRELATION OF SMALL-SCALE SEDIMENTARY CYCLES FROM BASIN TO STRANDLINE, GREENHORN CYCLOTHEM, WESTERN INTERIOR, U.S.

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High-resolution stratigraphic analysis shows that small-scale (21-100 Ka) sedimentary cycles in the late transgressive phase of the Late Albian–Middle Turonian Greenhorn Cyclothem can be traced from the south-central part of the Western Interior basin in Colorado to its clastic western margin in southern Utah. In the central basin, the sedimentary cycles are represented by 0.5–1.0 m thick bedding couplets with a relatively clay-rich lower unit (calcareous shale) and a relatively carbonate-rich upper unit (marlstone or limestone). In a westward direction the carbonate-rich portions of these couplets grade into fossiliferous concretion beds and shell lag accumulations that display evidence of sediment omission and bypass. Immediately seaward of the strandline these concretions and shell beds can be traced into bioturbated, fossil-rich, transgressive lag deposits that overlie coarsening-upward progradational strand plain units (parasequences), each of which varies from approximately 10–20m in thickness at the most proximal localities observed. These progradational deposits are correlative to the clay-rich portions of the central basin couplets.

Seven of these small-scale cyclothems in the Greenhorn Limestone have been correlated from the central basin to the strandline. The correlations have been confirmed by chemical fingerprinting of volcanic ash beds that bracket the cyclothems across the east-west transect. These correlations suggest that limestone formation in the central basin resulted from cut-off of clastic sediment supply and concentration of pelagic carbonate which occurred during short-term transgressive pulses of the strandline. Because the shale-limestone couplets of the Bridge Creek Limestone Member have been widely regarded as examples of Milankovitch climate cycles (estimated sedimentation rates and geochronology suggest approximate periodicities of 20–100 Ky), these correlations have significant implications for models of sedimentary cyclicity. Possible climate-related hypotheses for their formation include: a) short-term eustatic fluctuations related to variations in continental ice volumes; b) thermal expansion and contraction of oceanic water masses; and/or c) changes in sediment supply related to alternating wet/dry periods. In addition, tectonic activity related to thrusting in the

# TRACE-FOSSIL RECORD OF REDOX CYCLICITY IN THE NIOBRARA FORMATION

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Typically, the only evidence for the presence of predominantly soft-bodied, infaunal organisms preserved in the stratigraphic record is an assemblage of biogenic sedimentary structures, or trace fossils. Although the specific producers of biogenic structures are rarely known, trace-fossil assemblages are sensitive indicators of the response of organisms to paleoenvironmental parameters. In fine-grained marine pelagic and hemipelagic strata, trace fossils provide a particularly good indication of bottom- and/or pore-water redox conditions. Specifically, trace-fossil diversity, burrow diameters, and depths of burrow penetration generally decrease as benthic oxygenation deteriorates. When synthesized into a trace-fossil tiering model and applied in detailed vertical sequence analyses, these trends can be used to construct paleo-oxygenation curves that reflect relative degree of oxygenation as well as the rates and magnitudes of temporal change thereof. Hence, trace-fossil studies are particularly useful for assessing redox events and cycles in the rock record.

The Upper Cretaceous Niobrara Formation is characterized by interbedded laminated strata, which reflect anaerobic conditions, and bioturbated strata, which reflect periods of improved oxygenation. Bioturbated intervals are characterized by one or more of five ichnofossil associations: the 1) *Chondrites*; 2) *Zoophycos*; 3) *Planolites*; and 4) *Thalassinoides* associations. The characteristics of these associations (Table 1) suggest that they represent oxygen-related ichnocoenoses. Placed in the context of trace-fossil tiering, the vertical disposition of these ichnocoenoses has been used to construct paleo-oxygenation curves. Curves for the Fort Hays Member reflect high magnitude redox cycles characterized by rapid deoxygenation and gradual reoxygenation. Curves for the Smoky Hill Member reflect background conditions. Concomitant increases in interpreted oxygenation levels and carbonate contents support the combined redox-dilution model for the Niobrara cycles, and are consistent with a wet/dry climate forcing mechanism. Estimated cycle periodicities of 19 to 22 ky for both the Fort Hays and Smoky Hill Members suggest that redox-dilution variations were modulated principally by the Milankovitch cycle of precession.

active Sevier orogenic belt could have resulted in rapid subsidence events and transgression of the strandline; some of the cyclothems may have been produced, or their expression enhanced, by this mechanism.

Table 1. Characteristics of Laminated Strata and Ichnofossil Associations in the Niobrara Formation. A: number of common, recurring ichnogenera; B: maximum burrow diameter (mm); C: maximum discernible burrow penetration depth (cm); D: organic carbon content (wt. %); and E: carbonate content (wt. %).

| Ichnofossil Association | A | B | | C | | D | | E | |
|---|---|---|---|---|---|---|---|---|---|
| | | Ave. | Range | Ave. | Range | Ave. | Range | Ave. | Range |
| Laminated | - | - | - | - | - | 2.10 | 0.90-2.80 | 47 | 34-66 |
| *Chondrites* | 1 | 1.0 | 1 | 3.5 | 3-4 | 0.60 | 0.25-0.95 | 48 | 40-56 |
| *Zoophycos/ Teichichnus* | 2-3 | 3.7 | 2-6 | 6.5 | 3-18 | 0.38 | 0.20-0.60 | 58 | 42-79 |
| *Planolites* | 3-4 | 6.4 | 4-13 | 13.0 | 8-19 | 0.20 | 0.08-0.42 | 69 | 38-96 |
| *Thalassinoides* | 4-5 | 11.2 | 7-15 | 24.8 | 11-45 | 0.13 | 0.08-0.20 | 90 | 79-96 |

# SEDIMENTARY, BIOTIC AND GEOCHEMICAL CYCLES IN THE BOREAL CRETACEOUS: INTRODUCING A MULTI-DISCIPLINARY DRILLING PROJECT IN NORTHERN GERMANY (THE BOREAL CRETACEOUS CYCLES PROJECT - BCCP)

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An interdisciplinary working group is investigating sedimentary, biotic and geochemical cycles in the Boreal Cretaceous. As a key area the Cretaceous NW-german basin was selected. This basin offers unique possibilities to study sequences and cycles of various scale and allows furthermore the discrimination between eustatic and tectonically controlled transgressive/ regressive cycles. In addition to outcrops, a suite of boreholes (covering the entire Cretaceous sequence) combined with an extensive logging program and additional excavations will allow us to understand the general and regional factors controlling these cycles.

Our ultimate result should be an interdisciplinary paleoenvironmental analysis allowing a comparison between tethyan and boreal depositional environments and the pattern of cyclicity. A comparison/correlation of the cyclicity patterns of the boreal and tethyan realm (e.g. Gubbio area (Italy), NW-African Coastal Basins) in a future phase of the project should enable us to test whether the various cycles are synchroneous and global or not.

Details of our ongoing investigations include:

(1) Influence and effects of rhythms and paleoceanographic events on sedimentary sequences.

(2) Black shale sedimentation and anoxic events.

(3) Discrimination of Milankovitch-Cycles; with special emphasis on the Lower Cretaceous "light-dark" sediments.

(4) Eustasy and epirogenetic movements (periodicity of 10 Ma?).

(5) Tethyan influences in the faunal/floral record.

(6) Influence of global Bio-Events.

This project is Germany's principal contribution to the CRER/GSGProgram.

# RHYTHMIC BEDDING OF DEPOSITIONAL STRUCTURES AND EARLY DIAGENETIC MINERALIZATION IN THE CHALK OF THE MAASTRICHTIAN-TYPE LOCALITY

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A classical sequence of rhythmically bedded upper Maastrichtian carbonates is exposed in several quarries near Maastricht (S. Limburg, The Netherlands). The 100-m thick succession is characterized by a gradual upward coarsening from coccolithic mudstones (chalk) towards bioclastic sands (tuff chalk, Maastrichtian s.s., Dumont 1849).

The sequence reflects the gradual rotation and tilting of the northern flank of the Ardennes Massif during Upper Maastrichtian times. It has been fully preserved, despite the syn-depositional tectonics, and it records the change from a muddy littoral towards a shallow, sandy self-depositional environment. A total of 140 cycles have been distinguished. They are grouped in clusters of 5, 10 and 20. The rhythms are expressed by variations of fossil associations, bed thickness, grain size, depositional structures and early diagenetic mineralizations, such as silica concretions, carbonate cement, clay minerals, glauconite, pyrite, manganese and phosphate.

Quantitative analyses of sieve fractions, thin sections and digitized photographs of the bedding rhythms, demonstrate a complex relation between the various lithologic parameters.

The gradual changes of these parameters are attributed to changes of intensity and character of water movement and turbulence during the Upper Maastrichtian. Oscillations of mean kinetic water energy, superimposed on long-term trends, were caused by varying intensity and frequency of storms, which followed a Milankovitch periodicity. This caused ordered cyclic bedding as the result of periodic variations of sedimentation rate, depth of sediment reworking, depth of oxygen and sulphate diffusion, depth and type of bioturbation and of bacterial metabolism favouring specific mineralization.

A model will be presented that explains the dynamics of the deposition of the cyclic chalk succession, and that draws attention to the role of early diagenesis and the relation with hydrodynamics.

Examples of chalk sequences exposed near Maastricht, along the Gironde estuary (SW France) and at Stevns Klint (Denmark), do support the proposed model and will be discussed.

# FLUID- AND ROCK-DOMINATED SULFIDE DIAGENESIS OF THE ALBIAN HARMON MEMBER, WESTERN CANADA

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The Albian Harmon Member (Peace River Formation) comprises three lithofacies: laminated mudstone (LM), laminated to bioturbated siltstone (LBS) and interbedded conglomerate and mudstone (ICM). LM results from hemipelagic sedimentation under dominantly anoxic conditions. LBS was deposited below storm wave base more proximal to the basin margin under dysaerobic to anoxic conditions. ICM represents high energy, episodic deposition as turbidites or tempestites. The rapid to episodic depositional nature of LBS and ICM, compared to the slower, steady rate of deposition for LM lithofacies, is interpreted to be a primary control on the carbon, sulphur, and iron systematics of the sediments and the morphology and isotopic composition of early diagenetic pyrite.

Pyrite in LM lithofacies is homogeneously distributed and occurs almost exclusively as discrete framboids less than 20μm in size. LM lithofacies is further characterized by relatively constant carbon-sulphur ratios, iron-sulphur ratios, and $\delta^{34}S$ values for pyrite that indicate fluid-dominated conditions (high water-rock ratios) during sulphate reduction and subsequent pyrite formation. Evaluation of organic matter (OM) maturity and hydrogen indices (HI) suggest that OM reactivity limited sulphate reduction in these sediments.

Pyrite in LBS and ICM lithofacies (transition zone) generally is distributed heterogeneously and occurs as framboidal, zoned, or massive aggregates up to 400μm in size. Transition zone sediments have extremely variable carbon-sulphur and iron-sulphur ratios and pyrite $\delta^{34}S$ values. Pyrite in these sediments is enriched in $^{34}S$ relative to LM sediments, indicating that the exchange of sulphate between pore-waters and the overlying water column was restricted, with sulphate reduction sometimes occurring under rock-dominated conditions (low water-rock ratios).

Calculations using a simple Rayleigh distillation model indicate that water-rock ratios in transition zone sediments under rock-dominated conditions are estimated to have been between 1 and 110 during sulphate reduction and subsequent pyrite formation. Some samples have $\delta^{34}S$ values close to or greater than Albian seawater, indicating virtual closed-system conditions with respect to sulphate.

# OCEANWIDE ANOXIA IN THE EARLY APTIAN

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A high resolution combined foraminifera and nannofossil biostratigraphy has been derived for the Aptian-Albian interval. A detailed analysis has been carried out of the age of organic carbon-rich horizons deposited in land and DSDP/ODP sections on a global basis. One interval in which such horizons tend to cluster is the early Aptian, and we propose this interval as an oceanic anoxic subevent (OASE). The early Aptian OASE lies within the *G. Blowi* foraminifera zone and *C. litterarius* nannofossil zone and corresponds to the occurrence of complex positive and negative excursions in $\delta^{13}C$. Even though this interval is very brief with respect to the Cretaceous as a whole, both biostratigraphy and isotope stratigraphy indicate that this OASE may have been slightly time-transgressive. This suggests a combination of local and ocean-wide causal mechanisms. Preservation of organic material is clearly a crucial factor in the origin of this OASE. The proposed OASE correlates with a highstand or transgressive sea level episode. The early Aptian OASE bears some resemblance to the Cenomanian-Turonian boundary OAE, however there are biotic and geochemical differences.

# TRACE METALS IN CRETACEOUS BLACK SHALES

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Many Cretaceous black shale sequences, especially those from the Cenomanian/Turonian Boundary Event (CTBE or OAE 2) are characterized by the enrichment of specific trace metals, in particular Ag, Cd, Mo, Zn, V, Cu, Ni and others. The questions which have to be answered are:

1. Why are these elements accumulating in TOC-rich sediments and what is their origin?

2. May trace metals serve as indicators of the environment of deposition of Cretaceous black shales?

3. Do "global" black shale events influence the exogenic cycle of elements?

Under present-day oceanographic conditions, many trace metals are highly involved in nutrient-like regeneration processes. Metals like Cd, which shows a distribution similar to P in seawater, at present are only accumulated in areas of high productivity and rapid burial and not in deep-sea environments. Therefore, plankton chemistry and water column regeneration are responsible for the specific composition of upwelling sediments.

The occurrences of many CTBE black shales in deep-water settings and the combination of low sedimentation rates and high TOC and trace metal contents favour deposition of these strata under severe oxygen depletion in the ocean. Water column regeneration must have been suppressed and early diagenetic (Mo, V, U) as well as authigenic (metal-sulfide precipitation) element enrichment proceses are important factors.

Simple mass balance considerations reveal that seawater alone does not explain element abundances in CTBE black shales. Fluvial and hydrothermal (Zn) input are important metal sources. By making assumptions about the metal input rates, a time frame for the duration of the CTBE (0.3 to 1 Ma) can be given.

# GEOCHEMICAL EVIDENCE FOR GLOBAL CHANGES IN ORGANIC-CARBON BURIAL AND PALEOCEANOGRAPHY AT THE CENOMANIAN/TURONIAN BOUNDARY

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One of the most significant events in the Cretaceous record of organic carbon (OC) burial is the short (<1 m.y.) but intense period of global organic productivity and OC burial that accompanied a major global rise in sea level at the Cenomanian/Turonian (C/T) boundary (about 91 Ma). The C/T event was nearly synchronous throughout the Atlantic and Tethys basins as well as in high latitude epicontinental seas. The increased rate of OC burial resulted in massive transfer of carbon from the oceans and atmosphere to marine sediments that contain as much as 50% OC in some areas. This massive removal of isotopically light ($^{13}C$-depleted) OC is recorded as a progressive increase in $\delta^{13}C$ of carbonate carbon by an average of about $2^{o}/_{oo}$ and as an increase in $\delta^{13}C$ of marine organic matter from values of about -27 to $-28^{o}/_{oo}$ (typical of pre-C/T organic matter) to values as high as $-21^{o}/_{oo}$ at the C/T boundary. We calculate that the increased rate of OC burial at the C/T boundary was sufficient to strip the atmosphere of $CO_2$ within several hundred thousand years. These calculations ignore feedback from oceanic and crustal carbon reservoirs but do suggest that there may have been a significant reduction in $pCO_2$ at the C/T boundary. A reduction in $pCO_2$ has two major implications. First, lower $pCO_2$ may have caused global cooling, as suggested by the oxygen isotopic composition of inoceramids from northwest Europe. Second, decreased availability of dissolved $pCO_2$ may have affected the isotopic fractionation of OC by phytoplankton, as suggested by experimental studies. The C/T event illustrates how changes in tectonism and sea level can induce significant, rapid paleoenvironmental changes and biotic turnover that affect the partitioning of carbon between sediment and oceanic reservoirs.

# TIMING AND PALEOCEANOGRAPHY OF APTIAN-ALBIAN ANOXIC EVENTS FROM ITALIAN SEQUENCES: THE CONTRIBUTION OF CALCAREOUS NANNOFOSSILS

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The Aptian-Albian formations widely outcropping in Italy contains numerous black shale layers. Particularly, more than one hundred anoxic events are consistently recorded in the Scisti a Fucoidi through the Umbrian-Marchean Basin, whereas only a few black shale layers are interbedded in coeval formations from the Lombardy Basin (Marne di Bruntino) and the Gargano region (Scaglia Bianca).

The time control of the black shale deposition was achieved applying the nannobiostratigraphy proposed for the Piobbico core and routinely integrated with the planktonic foraminiferal zonation. The biostratigraphic framework allows the identification of three discrete anoxic events during the Aptian-Albian; moreover the Albian is characterized by rhythmic black shale deposition.

The late Early Aptian "Livello Selli" is a thick and $C_{org}$-rich black shale considered as a regional marker through the Umbrian-Marchean Basin. Analogous coeval layers were identified in a few sections outcropping in the Lombardy Basin. Two other thick and $C_{org}$-rich black shales are dated to the latest Aptian ("Livello 113") and Early Allbian ("Livello Urbino") respectively. They are also recognizable throughout the Umbrian- Marchean Basin and the older is correlated to an anoxic event recorded in the Gargano area. As in the Umbrian-Marchean Basin, in the eastern deepest portion of the Lombardy Basin the Middle and Late Albian is represented by rhythmic black shale deposition.

Quantitative study of the calcareous nannofossil content gives some constraints to the paleoceanographic interpretation of black shale events. The "Livello Selli" is a carbonate-depleted black shale and is barren of nannofossils. The nannofossil assemblages of the "Livello 113" show intense diagenetic modifications, but slight evidence of increased fertility was pointed out. The nannofloras of the "Livello Urbino" are clearly characterized by an increase in abundance of the fertility indices (*Biscutum constans* and *Zygodiscus* spp.). The nannofossil assemblages of the rhythmic black shales point to moderate fertility in warmer waters.

Nannofossil distribution was correlated with sedimentologic, geochemical, foraminiferal, and radiolarian data. The resulting picture is as follows: (a) the three discrete anoxic events are related to higher delivery of organic matter to the sea floor under vigorous upwelling; (b) the rhythmic black shales seem to have occurred during times of decreased total organic productivity, and the organic matter was probably preserved because of poor ventilation at depth.

# PROCESSES CONTROLLING THE DEPOSITION OF THE SHARON SPRINGS MEMBER OF THE PIERRE SHALE DURING THE EARLY CAMPANIAN

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Total organic carbon concentrations (up to 13 weight %) for the Sharon Springs Member of the Pierre Shale are among the highest for organic-rich rocks deposited in the Cretaceous Interior Seaway. The organic characteristics and distribution of the Sharon Springs are controlled by the interactions of eustasy, subsidence, climatic, and to a lesser extent, oceanographic conditions.

First-order control on organic-rich rock deposition was provided by the formation of a semi-restricted epeiric sea resulting from the development of a foreland basin during a period of high sea level in the mid-Cretaceous. Second order controls are related to the interaction of second- and third-order eustatic rises with major subsidence events that were ultimately related to compressional tectonic events on the western side of the seaway. The interaction of eustacy, subsidence and climate primarily controls the ***concentration*** of organic matter. The timing and nature of compressional events, and intervening quiescent phases, controlled the location and areal extent of condensed sections and hence the area where organic-rich rocks can be concentrated. A number of the Cretaceous organic-rich rocks in the Interior Seaway were deposited during periods of higher rates of relative sea level rise associated with a phase of active loading to the west. The Sharon Springs is an exception since the time of deposition does not appear to be related to an active phase of thrust related to tectonic loading in the orogenic belt.

During the early Campanian, an increase in subsidence rates in the central portion of the Campanian seaway is interpreted to have been induced by sediment loading (flexural) during a tectonic relaxation phase. The high subsidence rates coincided with a eustatic rise during the ZC4.1 cycle (~80Ma). The resulting Claggett transgression significantly increased water depths across the basin, reduced the supply of terrigenous material and produced a widespread condensed section. There is no apparent increase in subsidence rates in the eastern part of the seaway near the depositional limits of the Sharon Springs Member. Water depths in the deepest part of the basin reached at least 180m, which was sufficient to allow stratification and ***preservation*** of organic matter. Increased supply of nutrients during the transgression and expansion of warm subtropical waters into the Western Interior Seaway may have enhanced organic matter ***productivity*** during the deposition of the Sharon Springs.

# OXYGEN MINIMA AND ORGANIC-RICH SEDIMENTS: IS THERE A CAUSATIVE RELATIONSHIP?

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This paper disputes the oft-advanced arguments that oxygen minima promote the preferential accumulation of organic-rich sediments on continental margins. A number of specific cases in the modern ocean will be presented which demonstrate that the bottom water oxygen concentration has little or no effect on the rate of accumulation of organic carbon in the underlying sediments. First, new data from surface sediments on the productive Oman Margin in the northwest Arabian Sea show that organic carbon contents are controlled by primary production and hydrodynamic factors (winnowing, as indicated by the areal distribution of the sedimentary Cr/Al ratio) rather than by the impingement of the regionally severe oxygen minimum on the continental margin. There is no significant relationship in this area between the extremely low bottom-water oxygen content and either the organic carbon concentration or its state of preservation, the latter indicated by C:N ratio and Rock-Eval pyrolysis data. Second, the coincidence of the oxygen minimum in the Gulf of Mexico with a zone of high organic carbon contents is shown to be best explained by the interplay between the sediment texture, dilution and the decreasing settling flux of carbon with increasing water depth on the slope. Third, organic carbon maxima on the northeast and northwest Atlantic continental slopes are unrelated to the position of the oxygen minima. Fourth, surface sediments under the oxygen minimum in the Gulf of California are not enriched in organic matter when compared to adjacent deposits above and below the minimum which are accumulating under oxygen-replete conditions. We conclude that the formation of organic-rich sediments on continental slopes is essentially unrelated to the presence or absence of an oxygen minimum at these depths.

# HIGH-RESOLUTION PALEOECOLOGICAL RECONSTRUCTION OF CRETACEOUS BLACK SHALE FACIES

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High-resolution stratigraphic studies of Mesozoic organic-rich facies have yielded diverse data on the nature and distribution of benthic macroinvertebrate-dominated communities and their special adaptations to ancient oxygen-deficient marine environments. These data include the adaptive characteristics, life habits and trophic strategies of individual species, as well as population structure, trends in diversity and abundance, and biostratinomy of benthic communities. Consideration of analogous data from modern low oxygen-adapted communities has allowed development of actualistic models for the ecology of paleocommunities in oxygen-deficient facies. Using examples from the Late Albian to Lower Campanian Greenhorn and Niobrara Cyclothems in the Western Interior Basin of North America, the following relationships between benthic communities and their environments can be demonstrated: (1) Virtually all Western Interior black shales and related organic-rich facies contain resident low diversity benthic communities which are composed predominantly of: a) detritus-feeding infaunal taxa; or b) broad, flat epifaunal bivalves (flat clams) acting as shell islands for simple epi- and endobiont microcommunities. The two community types interface under upper dysaerobic conditions, but occur independently in many black shale facies representing lower benthic oxygen levels. This suggests two discrete models for benthic conditions, one with the redox boundary within the sediment, and another with it situated at the benthic boundary interface. Substrate conditions may play a key role in which type is present in a given sequence. (2) A series of special adaptations to very low oxygen levels and soft substrates have been identified in the resident faunas and include, among bivalves, broad, thin shells, enlarged gill and mantle absorptive areas, and chemosymbiotic trophic strategies. (3) There is a gradient of benthic biofacies, defined predominantly on adaptive strategies, life habits and community diversity, that characterizes different levels of oxygenation through the dysoxic structure indicating resident or event communities (and thus the nature and duration of benthic oxygen states) these biofacies allow detailed sensing of paleo-oxygen histories in organic-rich sequences. (4) By mapping the distribution of biofacies in vertical sections, as well as across basinal transects, a hierarchy of apparent oxygen depletion and recovery events ranging from short-term (1 to 10 yr) to long-term (>1 My) can be identified. Collectively, these paleoecological factors reflect a dynamic oceanographic history in the Western Interior sea and allow rejection of a stagnant basin hypothesis. Their recognition demonstrates the power of high-resolution studies in paleoenvironmental reconstruction or organic-rich facies.

# BIOCHRONOLOGY AND BIOLOGIC CHARACTERIZATION OF APTIAN TO TURONIAN ORGANIC-RICH SEQUENCES

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Cretaceous strata of Aptian-to-Turonian age record several episodes during which sediments rich in organic carbon were widely deposited. Three prominent episodes occurred during the early Aptian, Aptian to Albian, and Cenomanian to Turonian. Results from high-resolution, integrated foraminiferal and nannofossil stratigraphy show chronologic and biologic similarities and dissimilarities between these episodes. The early Aptian and Cenomanian-to-Turonian episodes are short events; each lasted less than 1 m.y., and each is associated with a single planktic foraminiferal zone. Both are represented by condensed sequences of black shales that are interoceanic and possibly global in distribution and occur in deep- and shallow-water environments.

The Aptian-to-Albian episode consists of a more complex, less well-defined sequence of more than 2-m.y. duration that contains several black-shale intervals. Although organic sediments associated with this episode are widespread, the unique planktic foraminiferal assemblage within this zone is occasionally found in Pacific and Atlantic pelagic sequences devoid of black shales.

Each of the three episodes is characterized by unique patterns in planktic foraminiferal extinction and survival, species diversity, specimen size, and morphotypes associated with specific water depths. The early Aptian episode had little effect on the low-diversity, largely surface-dwelling population of small planktic foraminifers, whereas the later episodes show the extinction of severe reduction of large, deeper water forms. Each of the episodes was followed by a period of adaptive radiation: the early Aptian episode was followed by the first appearance of medium-size planktic foraminifers; the aptian-to-Ablian episode was followed by a gradual and fluctuating increase in species diversity and specimen abundance and the reappearance of large, intermediate-water forms; the Cenomanian-to-Turonian episode was followed by a dramatic, rapid diversification of large deep-water forms and the sudden reappearnce of other deep- and intermediate-water species. Although these effects can be explained in terms of water-column stability, chemistry, and productivity, further biologic comparisons of these and other organic-rich sequences are required to better understand their origin.

# SULFUR ISOTOPIC EXCURSION AT THE CENOMANIAN-TURONIAN BOUNDARY RECORDED BY PYRITE AND ACID-VOLATILE SULFIDES

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Sulfur isotopic values of pyrite and acid-volatile sulfide (AVS) show a negative excursion of about $14^{o}/_{oo}$ across the Cenomanian-Turonian boundary in outcrop samples collected at Pueblo, Colorado. The shift in sulfur isotopic values occurs in both limestones and marlstones. Although only a minor fraction of total sulfur, the acid-volatile sulfide is consistently heavier than pyrite (average difference $5.9^{o}/_{oo}$) and parallels the pyrite curve. Plots of organic carbon (0.12–4.50 wt.%) versus total sulfur (.20–1.23 wt.%) yield a slope similar to the normal marine line for samples with organic carbon contents less than 1.5%. Samples with higher contents of organic carbon show little variation in sulfur content (average 0.81%) and appear to be iron-limited in terms of sulfide formation. The degree of pyritzation (DOP) is moderate to high throughout the studied section.

A negative shift in sulfur isotopic values from about $-25^{o}/_{oo}$ to $39^{o}/_{oo}$ suggest a change in the position of the zone of bacterial sulfate reduction. The unusually negative values at the peak of the excursion indicate sulfate reduction at, or above, the sediment-water interface, under conditions open to sulfate, resulting in a maximum expression of biological fractionation. The heavier values above and below the excursion indicate sulfate reduction below the sediment-water interface under diffusion-limited conditions. The heavier isotopic values of AVS compared to pyrite probably result from formation of a ferrous monosulfide after the peak of pyrite formation.

The sulfur isotopic excursion spans the Cenomanian-Turonian boundary, based on macrofossils, and occurs within the upper half of the global excursion in carbon isotopic values. The direction and magnitude of the sulfur isotopic excursion suggests a basinal response to paleo-oceanographic conditions rather than a global response to increased burial of organic matter that would have resulted in a positive shift of sea-water sulfate due to formation of isotopically light pyrite.

# CORAL-DOMINATED FRAMEWORKS ACROSS CRETACEOUS CARBONATE PLATFORMS

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The stratigraphic and physiographic distribution of coral-dominated frameworks can be illsutrated through selected examples of Cretaceous carbonate platforms from the Caribbean and Mediterranean Tethyan provinces. Six major coral-dominated assemblages can be distinguished on the basis of the relative abundance of the preserved biota: corals, rudists, red and green algae, microbial communities (i.e. cyanobacteria and bacteria) and, to a lesser extent, calcareous sponges and hydrozoa, as follows:

(1-2) Coral and coral-stromatoporoid-hydrozoan assemblages typically occur in the outer part of Early Cretaceous platforms (Berriasian-Aptian) in cases where rudist-dominated assemblages are restricted to the inner, platform zone.

(3) Coral-microbial assemblages form biostromes and bioherms. In some cases referred to as mud mounds, in deeper parts of Barremian to Cenomanian platforms or ramps.

(4-5) Coral-algal-microbial and sponge-algal-rudist-coral-microbial assemblages are unusual and occur in restricted depositional environments (low energy, low illumination, and/or oxygen-depleted environments) on Turonian-Coniacian platforms of the Mediterranean Realm. (Camoin, G., 1989, Thes. Doct. es-Sci., Marseille, 899 p.; Camoin, G., 1989, Third Symp. Ecol. Paleoecol, Benth.-Comm. Catania, 333-358). The abundance of encrusting organisms and the proliferation of microbial communities should be related, as for (3) above, to an excess of nutrient availability.

(6) Coral-algal-rudist assemblages are important parts of Albian (Caribbean) and Santonian to Maastrichtian (Mediterranean) biostromes and bioherms on shelf margins and isolated platforms. (Camoin, G., 1988, Sedimentology, 35, 123–138; Camoin, G. et al., in press, Bull. Soc. Geol. France).

In contrast to modern coral reefs, Cretaceous "reef" frameworks were linked to carbonate platform systems in which individual buildups are volumetrically limited, relatively to the surrounding sediment, and exhibit little topographic relief. In most cases, coral and rudist frameworks form distinct, commonly adjacent units on Cretaceous carboante platforms. Their differences in structure and paleoenvironmental setting probably reflect the different autecologies of the constituent bio-constructors. Throughout Cretaceous reef history, the diversification of reef ecosystems and the relative abundance of rudist- and coral-dominated frameworks were primarily controlled both by environmental factors and biotic interactions.

# NUTRIENT FLUX AS A REGULATING MECHANISM FOR REEF DEVELOPMENT: MODERN AND CRETACEOUS MODELS

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Nutrient flux impacts nearly every aspect of carbonate deposition, from evolution of carbonate-producing organisms to microfacies. Preceding patterns of nutrient flux and global nutrient gradients partly dictate whether reef-building organisms are present at any time in Earth history. During those episodes conducive to the evolution and persistence of reef-building organisms, nutrient regimes under which reefs developed are reflected in fossil makeup and diversity, rates and types of sediment production and accumulation, intensity of bioerosion, facies sequences, and composition and textures of carbonate accumulations.

Nutrient regimes determine major carbonate producers: plant-animal symbioses (mixotrophs) dominate benthic communities where nutrients are scarce, calcareous algae (autotrophs) dominate where nutrients are intermediate, and suspension-feeding animals (heterotrophs) dominate where nutrients are relatively abundant. Taxonomic diversity is generally inversely correlated with nutrient availability, though extremely low supplies also limit diversity of taxa with higher metabolic needs. In many taxa, size of individuals tends to increase when nutrient resources decline. Rates of sediment accumulation result from a complex interplay of mixotroph production, which declines with excess nutrients; autotroph production, which increases as nutrient supplies increase until light becomes limiting; and rates of bioerosion, which increase in response to increasing food supply. These factors strongly influence facies sequences, as well as sediment composition and texture. Carbonate buildups in low nutrient environments are dominated by skeletal grainstones and reefal framestones. As nutrient supplies increase, muds, pellets, and reworked clasts increase in predominance in response to algal production and bioerosion, while algal-bacterial mats at the sediment-water interface provide microenvironments for microboring, dissolution, and early cementation of sediments. Understanding the role of nutrient flux in modern carbonate depositional enviornments provides a basis for interpreting analogous facies in Cretaceous limestones, despite their very different fossil assemblages.

# CRETACEOUS REEFS AND PALEO-OCEAN CIRCULATION

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Cretaceous reefs have an unequal global distribution, suggesting significant regional differences in meridional heat transport by the ocean. Reefs occur on both sides of the Tethys, but they extend to much higher latitudes (50°S and ?N) in the western Pacific than along the coasts of the Americas in the eastern Pacific where they are restricted to the margin between 20°S and 30°N of the equator. The position of the Tethys, centered on 10° to 20°N and the complexity of its margins along with drifting terranes insures complex circulation patterns. The Northern Equatorial Current of the ancient Pacific would enter the eastern end of the Tethys but would then be directed northward where the increasing strength of the Coriolis force would tend to make it form cyclonic eddies. The Southern Equatorial Current of the ancient Pacific would be directed southward to bathe the coast of Madagascar and India with warm waters even though they lay at high latitudes. Cooler waters flowing equatorward along the eastern (American) margins of the ancient Pacific restricted the growth of reefs there. The reason that reefs on the South American margin are restricted to lower latitudes than those of the Central American margin is because the southern Pacific gyre traveled a greater distance through the polar region and experienced greater heat loss.

# CRETACEOUS PALEOBIOGEOGRAPHY OF RUDIST BIVALVES AND REEF ECOSYSTEMS IN THE CARIBBEAN PROVINCE

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During the Cretaceous the Caribbean Province was characterized by a dynamic interplay of tectonics and eustacy that controlled the development and distribution of carbonate platforms and influenced patterns of gene glow among tropical organisms. Caribbean Cretaceous reefs were initially built by coral-algal paleocommunities in Berriasian-Valanginian time but ecological dominance shifted to rudistid bivalves by the Albian. Stage by stage maps of the diversity and distribution of rudistid genera and reefs plotted on mercator projections and plate reconstructions trace the paleobiogeographic history of the Caribbean Province. These maps reveal centers of endemism and allow definition of paleobiogeographic subdivisions of Subtropical, Tropical and Supertropical zones defined on levels of generic endemism and diversity and the extent of framework building. The postulated Supertropical zone (Supertethys) lay between normal Tropical seas and was characterized by relatively higher temperature and salinity levels. This zone is thought to have existed episodically during warm Cretaceous intervals associated with eustatic highstand. When Supertethys was in place, a sharp change in taxonomic composition and diversity existed across the Supertethyan-Tethyan boundary; when Supertethys was not in place the boundary between the northern and southern tropics was gradational and paleobiogeographic differentiation declined. Aptian endemic centers were located in northern Mexico and in Trinidad/Venezuela. There was genetic isolation between these faunas, yet both are defined as Tropical suggesting a mid-Caribbean barrier. During Albian sea-level rise, generic diversity rapidly increased and Supertethys first appeared. The maximum development of Albian carbonate platforms and reefs was from Texas through southern Mexico. The endemic area of Trinidad/Venezuela continued to exist, and endemism initiated on the Chortis Block in the eastern Pacific. The Supertethyan zone persisted through the Cenomanian, as reflected in generic diversity and reef size, but became more constricted, resulting in net decrease in diversity. The Trinidad/Venezuela faunas disappeared by the Cenomanian, probably due to elimination of carbonate platforms by clastic drowning. The Chortis block remained isolated and retained its endemic biota. Following the Cenomanian mass extinction new genera and families appeared in the Turonian of Mexico, but Cenomanian-style faunas remained in the Antillean arc, suggesting genetic isolation between Mexico and the Antilles as the arc moved southeastward into the proto-Caribbean. Reef development was minor in the Coniacian and Santonian stages. Supertethys reappeared in the Campanian to the south of its Albian position, reflecting migration of the

Caribbean plate. The Campanian Supertethys was bounded on the north by a northern Mexican Tropical zone, south of the Gulf Coast Subtropical zone. The Maastrichtian was characterized by the greatest development of Antillean generic diversity and reef-building, just prior to Late Cretaceous mass extinction. The Campanian and Maastrichtian stages were characterized by a breakdown of genetic isolation within the Province as a result of emplacement of the Antillean plate. The proliferation of Caribbean Province rudist reefs only to the north of the Cretaceous paleoequator remains enigmatic.

# TEMPORAL AND SPATIAL DISTRIBUTION OF CRETACEOUS REEF COMMUNITIES ON CARBONATE PLATFORMS OF THE CARIBBEAN PROVINCE

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Throughout the Cretaceous, carbonate platforms of the Caribbean Province were characterized by shelf margin and platform reefs/frameworks of various types and composition. But individual reefs/frameworks never reached the size, diversity, and temporal stability of Cenozoic to Recent reefs, reflecting three factors: (a) The evolutionary time and environmental stability needed to develop complex reef-structured ecosystems in new Tropical seas (e.g. the Caribbean); complex-structured ecosystems apparently cannot be rapidly transplanted from a center of origin (i.e. Indo-Mediterranean Province) to a new, distal region (i.e. the proto-Caribbean) via planktotrophic larval drift; instead complex reef communities must develop independently from diverse immigrant stocks; (b) the highly dynamic nature of Cretaceous Caribbean history, with short-term alternations of intense tectonic/volcanic activity and relative quiescence, major sea-level fluctuations, episodic platform drowning and inundation by oxygen-deficient waters; these changes were superimposed on larger-scale plate tectonic movements, including the middle Cretaceous immigration of the Caribbean Plate into the proto-Caribbean; most Caribbean carbonate platforms did not persist for sufficient time to allow high levels of ecological diversification; and (c) early in the evolution of Caribbean reefs, ecological disruption of dominant earliest Cretaceous coral-algal reef communities due to Barremian-Maastrichtian competitive displacement and/or replacement by rudistid-dominated reef communities; this was coincident with major changes in Caribbean ocean/climate systems. A system of classification for Caribbean Cretaceous reefs/frameworks is proposed, based on the relative abundance and integration of bioconstructors, and the shape and size of the structures. The majority of known Cretaceous reefs/frameworks in the Caribbean Province have been mapped and classified within this system. These have yielded diverse data on adaptive morphology, taxonomic composition, community distribution, and ecological succession/sequencing of reef communities. These data have been plotted on Caribbean carbonate platform reconstructions within stage-level time slices, platform margin to shoreline biotic zonations established, and the evolution of framework/reef ecosystems interpreted. Marked changes are seen in reef character and distribution through the Cretaceous, including overall increase in the diversity of bioconstructors, epi- and endobionts, and diversification of framework types into all major carbonate platform facies.

# FORAMINIFERAL DISTRIBUTION PATTERNS AND CONTROLLING MECHANISMS ACROSS MID-CRETACEOUS CARBONATE SHELVES FROM LOW-LATITUDE WESTERN ATLANTIC REGIONS

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Foraminiferal distribution patterns allow reconstruction of the paleoceanography and paleogeography of middle Cretaceous carbonate shelves from low-latitude western Atlantic regions. A case study is presented from two Cretaceous carbonate-dominated sequences: (a) The Sergipe Basin (Late Aptian – Early Coniacian) of northeastern Brazil; and (b) the Gulf of Paria area (Aptian) from offshore eastern Venezuela (data from E.A. Koutsoukos and K.A. Merrick, 1986, Foraminiferal Paleoenvironments from the Barremian to Maastrichtian of Trinidad and Tobago, p. 85-101). Thirteen benthonic foraminiferal paleocommunities are empirically recognized in these successions, based on the distribution patterns of well-defined species assemblages grouped at the family level. These are related to variations in inferred trophic structure, substrate niche patterns (paleobathymetry; microhabitats), and benthic oxygen levels, as follows:

<u>Epifaunal and shallow infaunal taxa</u>: Passive herbivores (browsers) and active deposit feeders (grazing herbivores, detritivores, omnivores)

(1) Involutinidae (Aptian-Albian, aerobic, oolitic-oncolitic shoals and algal patch reefs)

(2) Cyclamminidae-Trochamminidae-Vaginulinidae (Early–Late Aptian; dysaerobic lagoonal biotopes)

(3) Lituolidae-Haplophragmiidae-Cyclamminidae (Late Aptian – earliest Albian; aerobic-dysaerobic lagoonal biotopes)

(4) Trochamminidae-Discamminidae (Cenomanian–Early Turonian; aerobic-dysaerobic, inner-middle shelf biotopes)

(5) Gaveliniellidae-Conorbiodidae-Spirillinidae-Patellinidae (Late Aptian–Middle Albian; Early–Middle Cenomanian; Late Turonian; aerobic inner - middle shelf biotopes)

(6) Gavelinellidae-Epistorminidae-Vaginulinidae (Early Aptian–Middle Albian; dysaerobic middle-outer shelf biotopes)

(7) Gavelinellidae-Alabaminidae-Vaginulinidae (Late Albian–Early Cenomanian; aerobic-dysaerobic outer shelf biotopes)

(8) Gavelinellidae-Bagginidae (Turonian–Early Coniacian; aerobic - dysaerobic, middle to outer shelf biotopes)

Infaunal Deposit Feeders (Bacterial and Detrital Scavengers)

(1) Vaginulinidae-Nodosariidae-Polymorphinidae (Late Aptian-Middle Albian; aerobic-dysaerobic, inner-middle shelf biotopes)

(2) Turrilinidae (Late Albian; Early Cenomanian; aerobic-dysaerobic, inner-middle shelf biotopes)

(3) Bolivinidae-Fursenkoinidae-Buliminellidae-Nodosariidae (latest Cenomanian through Late Turonian; dysaerobic outer shelf biotopes)

(4) Eggerellidae-Spiroplectamminidae-Textulariidae (Late Aptian–Middle Albian; dysaerobic middle-outer shelf biotopes)

(5) Ammosphaeroidinidae-Verneuilinidae-Spiroplectamminidae (Late Aptian–Middle Albian; dysaerobic outer shelf biotopes).

# MODELS OF CRETACEOUS CARBONATE PLATFORMS IN THE CARIBBEAN PROVINCE

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Cretaceous carbonate platforms in the Caribbean region began as small, areally restricted ramps and grew into very large pericratonic platforms during the Aptian and Albian. During the Late Cretaceous smaller, Tethyan-type platforms developed upon tectonic blocks and volcanic islands. The Early Cretaceous platforms were periodically drowned by low-oxygen sediments, but were re-established and prograded up to 15 km. Most platforms were finally terminated by a combination of sea-level fall and high input of siliciclastics from tectonic cratonic uplifts.

The Lower Cretaceous Comanchean Shelf extended from Florida to Mexico and to the Yucatan Peninsula. In Texas and Louisiana this platform consists of five major depositional-seismic sequences. The regionally extensive bounding surfaces of each are either drowning unconformities or exposure unconformities. Drowning is inferred where shallow shelf facies are overlain by deeper water pelagic facies. Exposure is inferred where coastal facies overlie marine shelf carbonates. The interval of downlap and maximum flooding may be either a sharp contact that corresponds with the sequence boundary, or it may be a gradational interval where deeper facies change to shoaling-up facies. Low angle, simple sigmoidal sequence geometry suggests low energy areas of the shelf. Steep, complex-oblique sequences suggest high energy areas.

Platform shelf communities experienced a dramatic change in community structure during the Cretaceous when rudists replaced the coral-algal community as the dominant reef builder. For about 30 Ma from the Hauterivian to the Albian, rudists coexisted with corals in shelf margin reef systems but each occupied separate habitats. Corals, algae, and stromatoporoids built the reef frame below wave base. Caprotinids, caprinids and radiolitids comprised the communities in the high energy wave zone. The elevator rudist niche so important in Late Cretaceous reefs was filled by caprinids during the Barremian through the Albian. Radiolitids became common in the Albian and were the main framework builders during the Cenomanian through Turonian. During the Campanian and Maastrichtian hippuritids were dominant. These later reefs were biostromes with frameworks of rudists; corals were a minor constituent of the biota.

This important change in reefal community structure had a major impact on the geometry of carbonate platforms. The platforms grew more by vertical accretion than by progradation. The demise of the coral-algal communities during the middle Cretaceous was the result of complex environmental changes and productivity cycles related to sea-level rise. During this time, the climate became more humid and atmospheric $CO_2$ increased. The concomitant environmental changes in oceanic conditions presumably stressed the deeper coral communities on reefs. The emergence of rudists as the major reef contributors profoundly changed the facies patterns of Cretaceous carbonate platforms.

# PALEOENVIRONMENTAL ASSESSMENT OF MICROFOSSIL ASSEMBLAGES ASSOCIATED WITH LATE CRETACEOUS CARBONATES AND PHOSPHORITES IN THE POTIGUAR BASIN, NORTH BRAZIL

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In the Potiguar Basin, at the equatorial margin of the Brazilian continental shelf, gamma ray profiles in the carbonate sequence of the upper Jandaira Formation (Turonian-Campanian) show a remarkable radioactive anomaly related to phosphorite layers. Paleoecological studies reveal that deposition of the phosphorite interval probably occurred in an area of upwelling of nutrient-rich bottom waters to the neritic zone during a major sea-level rise. The following events have been recorded: (1) Early Campanian termination of deposition on the shallow carbonate platform characterized by a diverse biota of ostracodes, micromolluscs, and algae; (2) Initiation of an Early to Late Campanian transgressive - regressive cycle characterized by composed of *Afrobolivina* at the base, and dominated by ostracodes and algae at the top; and (3) development of a second transgressive-regressive cycle during the Late Campanian. Phosphorites occur at the base of this Cyclothem and were deposited as the result of a large-scale sea-level rise that exceeded that of the first cycle. Within the cycle a rich benthonic foraminifer fauna developed and diversified; this fauna was dominated by Buliminacea. *Afrobolivina* dominates an assemblage which also contains smooth buliminaceans, epistominids, gavelinellids and sparse planktonic forms. In the middle and paleobathymetrically deepest phase of the cycle, smooth buliminaceans are dominant (*Neobulimina, Praebulima,* and *Buliminella*) with common *Lenticulina, Allomorphina, Gavelinella* and *Epistomina* associated with abundant keeled planktonic foraminifers. The upper part of the cyclothem is dominated by siphogenerinoidids with thick costellae (*Siphogenerinoides*).

# EMERGENCE AND KARSTING OF PACIFIC MID-CRETACEOUS GUYOTS, THE BIRTH OF THE DARWIN RISE, AND GLOBAL SEA LEVEL

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Mid-Cretaceous rudist reefs in the Northwest Pacific, over an area of about $3x10^6$ $km^2$ (about $10^7$ km, if Ita Mai Tai Guyot is included) show evidence of Late Aptian-Albian emergence of as much as 200 m prior to final drowning, probably in complexes (perimeter reefs enclosing lagoons and flanked by forereef talus) are commonly pocked by sinkholes and dolines, and some perimeters are partly circumscribed by low-stand terraces.

We associate the uplift with a major Late Aptian-Early Albian plate reorganization that speeded up and shifted Pacific Plate motion from southwesterly to northwesterly, and led to the creation of the Darwin Rise, which persists to this day as the Southeast Pacific Superswell. Regional thinning and heating of lithosphere in the southeast part of the Pacific Plate uplifted the seafloor and its superposed reef-capped seamounts. Subsequent northwest movement of the Pacific Plate gradually carried the emergent reefs off the Rise and drowned them, mostly in Late Albian time.

The global rise in sea level associated with the emergence of the reefs is estimated to be in the range 2–10 m. Because the emergence was at about the same time as the creation of major oceanic plateaus in the Pacific (Ontong Java, Manihiki, and Hess), whose displacement volume totaled about $3x10^6$ $km^3$, the combined effects of Aptian Pacific Plate sea-floor evaluation and mid-plate (plateau) volcanism amounted to about 10–20 m of eustatic rise.

Dredged fossils, magnetic surveys and radiometric dates from dredged volcanics supply our still-fuzzy timing constraints, which should be greatly sharpened by cores from ODP drilling scheduled on "MIT" Guyot for July 1990, and planned on other karsted Northwest Pacific guyots during future ODP legs.

# *Paleogeography, Paleoclimatology, and Sediment Flux*

# CRETACEOUS GLOBAL CLIMATE RECONSTRUCTION

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Plate tectonics and the capability to reconstruct continental positions and paleogeography have revolutionized paleoclimatology and paleoceanography by providing the basic spatial framework for climate reconstruction and analysis. The advances in paleogeography also coincided with rapid developments in climate modeling and with the development and application of a broad range of new techniques to examine the record.

The products of these advances are:

(1) physical predictions, independent of climate observations, of a wide range of climatic variables;

(2) three-dimensional views of the structure and characteristics of the atmosphere and ocean with a model interpretation of temporal variability;

(3) capability to compare observations with model output to evaluate model capability and to achieve new insights into the character and distribution of sediments;

(4) the opportunity for a comprehensive understanding of climate-sensitive sedimentary rocks;

(5) new capabilities to test climate hypotheses with the geologic record;

(6) the foundation for predictive capabilities with economic application;

(7) a basis for greater understanding of future global change.

The paleogeographic-paleoclimatologic research on the mid-Cretaceous illustrates many of these advances, including three-dimensional reconstructions of the ocean and atmosphere circulation and associated physical variables, a remarkable opportunity to compare observations with model output, and a strong foundation for predictive climate-sediment capability.

# $\delta^{18}O$, $\delta^{13}C$, AND $^{87}Sr/^{86}Sr$ TRENDS IN MAASTRICHTIAN FORAMINIFERAL SEDIMENTS FROM THE SOUTHERN OCEANS

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Isotopic reconstruction of Maastrichtian climates from pelagic sediments has been hampered by the lack of consistency in published records from widely distributed areas. This may be attributed to oceanographic differences on a global scale (i.e. different deep water sources), poor preservation of the foraminifera, and lack of chronological control in deep-sea sections, among other factors. $\delta^{18}O$ and $\delta^{13}C$ values of monospecific benthic and planktonic foraminiferal species from relatively complete Maastrichtian sections at Sites 689 and 690 on the Maud Rise in the Weddell Sea area show distinctive patterns that can be correlated with those from other southern latitude sections, indicating that they reflect regional or perhaps global conditions. The Maud Rise sediments have also been tied to the Geomagnetic Polarity Time Scale providing good time control and an excellent reference section.

Benthic and planktonic foraminiferal isotopic values from the Maud Rise fluctuate sympathetically. $\delta^{18}O$ values exhibit an increasing trend in the early Maastrichtian, increase sharply at the first of appearance of *Abathomphalus mayaroensis* at the base of the upper Maastrichtian and continue high thereafter. $\delta^{13}C$ values decrease in the early Maastrichtian with a sharp decline just before the *A. mayorensis* Zone, increase across the early-late Maastrichtian boundary and remain high in the late Maastrichtian. These patterns are also observed in the foraminiferal isotopic records of the shallow-water section at Seymour Island in the Antarctic Peninsula, and in deep-sea records from the southern South Atlantic. The increase in $\delta^{18}O$ values is interpreted as high latitude cooling, whereas the increase in $\delta^{13}C$ may be linked to the late Maastrichtian transgressive episode.

$^{87}Sr/^{86}Sr$ ratios at the Maud Rise show little variability averaging 0.707635±11 in the early Maastrichtian. (Ratios are adjusted to 0.71014 for NBS-987). Concomitant with the rise in $\delta^{13}C$, $^{87}Sr/^{86}Sr$ ratios increase sharply by about 0.00007 across the early-late Maastrichtian boundary, and then gradually by about 0.00005 in the late Maastrichtian into the early Tertiary. The cause of these rapid excursions in $\delta^{13}C$ and $^{87}Sr/^{86}Sr$ is not apparent but they may reflect oceanographic changes associated with a reported high turnover in benthic foraminiferal faunas near the early-late Maastrichtian boundary (Thomas, 1989).

# LATE MAASTRICHTIAN TO EARLY TERTIARY ENVIRONMENTAL CONDITIONS NEAR BRAZOS RIVER, TEXAS: FORAMINIFERAL STABLE ISOTOPE EVIDENCE

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$\delta^{13}C$ and $\delta^{18}O$ records of the planktonic foraminiferal species *Heterohelix globulosa* and the benthonic foraminiferal taxon *Lenticulina* spp. have been generated from a nearly continuous lower Maastrichtian (base of Chron 32.1N, 71.65 Ma) to lower Danian (base of Chron 28R, 65.5 Ma) section cored near the Brazos River, Texas. This sedimentary record comprising 25 m was deposited in middle to outer shelf depths. Foraminiferal preservation is excellent except for specimens from the earliest Danian Foraminiferal Zone PO. In the Maastrichtian interval $\delta^{18}O$ values of *H. globulosa* are invariably lower than those of the benthonic taxon by about 1 permil. Both records exhibit little agreement with conditions inferred based on the foraminiferal species population census. Two single-point negative $^{18}O$ excursions of about 1 permil near the base of Chrons C32.1N and C30N are not reflected in the population data. $\delta^{13}C$ values of the planktonic and benthonic taxa are very close reflecting either the planktonic species habitat within an oxygen minimum zone in the water column and/or vital effects of either taxa.

Isotopic ratios across the K/T boundary reflect global as well as local environmental conditions associated with the boundary event. Replacement of tests by secondary calcite did not significantly modify original isotopic signatures. $\delta^{13}C$ values decrease gradually by about 2.5 permil beginning at the K/T boundary, as defined by the first appearance of Tertiary planktonic foraminifera, and continuing approximately 40,000 years later (Zone PO/P1a). This gradual depletion contrasts with the sudden $\delta^{13}C$ drop of surface water total dissolved carbon at the K/T boundary observed in many deep-sea sections. At Brazos, the surface-to-bottom $\delta^{13}C$ gradient decreased to less than zero approximately 25,000 to 30,000 years after the K/T boundary and remained negative for at least the next 140,000 years. Concomitant with change in $\delta^{13}C$ values is a gradual decrease of about 2.5 permil in $\delta^{18}O$ values which has also been observed at the Agost section in Spain. This depletion suggests changes in temperature in the early Paleocene Gulf of Mexico. The high variability of foraminiferal isotopic values from Tertiary sediments indicates unstable environmental conditions which adversely affected the planktonic foraminiferal faunas and led to their decline and eventual extinction at the maximum isotopic depletion.

# CARBONATE-SILICATE CYCLE MODELING AT THE CRETACEOUS/ TERTIARY BOUNDARY

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The end-Cretaceous mass extinction events left the surface oceans largely devoid of ecosystems able to produce large amounts of pelagic carbonate. We studied the implications of this perturbation to the global carbonate-silicate geochemical cycle utilizing a number of models based on Broecker-type ocean box models embedded in BLAG-type carbonate-silicate cycle models. The fundamental result is that the models tend to suggest much more climatic sensitivity to changes in pelagic carbonate productivity than is suggested by paleoclimatic indicators, such as planktonic $\delta^{18}O$ data and paleobotanical evidence.

The relative climatic stability during the million years following the K/T boundary is suggestive of a feedback mechanism between reduced pelagic carbonate burial and other carbonate fluxes into or out of the oceans. Under ordinary circumstances, riverine and shallow-water carbonate burial fluxes regulate deep-water carbonate burial through the mechanism of shifting the calcite lysocline. However, after the K/T boundary, low pelagic carbonate productivity limited pelagic carbonate burial, which, absent other carbon-cycle feedbacks, would result in an ocean supersaturated with respect to calcite and very low atmospheric $CO_2$ levels. Evidence indicates that this did not happen, suggesting that there is a causal link between reduced pelagic carbonate sedimentation and reduced net fluxes of $Ca^{++}$ and $\Sigma CO_2$ to to the deep ocean. However, a clear mechanism has yet to be identified.

Evidence from DSDP/ODP cores suggest that, for several hundred thousand years after the K/T boundary, the pelagic carbonate sedimentation rate may have fallen to as little as 17% of the late-Cretaceous sedimentation rate. If the end-Cretaceous carbonate sedimentation rate was approximately half of today's rate, the reduction in pelagic carbonate sedimentation represents may have been on the order of $4 \times 10^{12}$ moles $CaCO_3$ $yr^{-1}$. Absent compensating mechanisms, a reduction in carboante sedimentation of this magnitude would saturate the oceans with respect to calcite on the time scale of $10^4$ yr, and could reduce atmospheric $CO_2$ below the compensation point necessary for photosynthesis on the time scale of $10^5$ yr. While the calcium compensation depth seems to have deepened during the Danian, the entire ocean does not seem to have become saturated with respect to calcite, and climatic indicators do not suggest a major cooling for several hundred thousand years that would be expected from radical reductions in atmospheric $CO_2$ levels.

Possible processes that could prevent calcite saturation of the deep ocean, and consequent reductions in atmospheric $CO_2$, include: (1) a decrease in riverine weathering fluxes; (2) an increased volcanogenic/mid-ocean-ridge $CO_2$ supply to the ocean-atmosphere system; (3) an excess in organic carbon weathering over organic carbon burial; and (4) increased shallow-water carbonate burial rates. Strontium isotope evidence suggests that terrestrial chemical weathering rates may have increased after the K/T boundary, so a reduction in riverine weathering fluxes does not seem a likely stabilization mechanism. An increased $CO_2$ supply, whether it be from increased metamorphism, mid-ocean ridges, or from an excess of roganic carbon weathering over burial, could temporarily sequester riverine cations in the oceans. However, as carbonate productivity was restored to the oceans the ocean-atmosphere system would be left with a surplus of carbon, producing very high atmospheric $CO_2$ levels (increases of over 1000 ppm, 500 kyr after the extinction events) which are not suggested in temperature proxy records. Both reductions in net organic carbon burial, or increased metamorphic/mid-ocean-ridge $CO_2$ fluxes without increased organic carbon burial, would tend to make the oceans isotopically lighter, i.e., decrease $^{13}C/^{12}C$ ratios. However, benthic $\delta^{13}C$ data suggest that the oceans may have become isotopically heavier. An attractive solution to this unresolved problem would be an increase in shallow-water carbonate sedimentation, coupled with increased organic carbon burial, compensating decreases in deep-water carbonate sedimentation and reduced pumping of $\Sigma CO_2$ from surface waters. However, there is as yet insufficient independent evidence to test this hypothesis.

# THE SOURCE OF CRETACEOUS DETRITAL SEDIMENT IN THE WESTERN NORTH ATLANTIC

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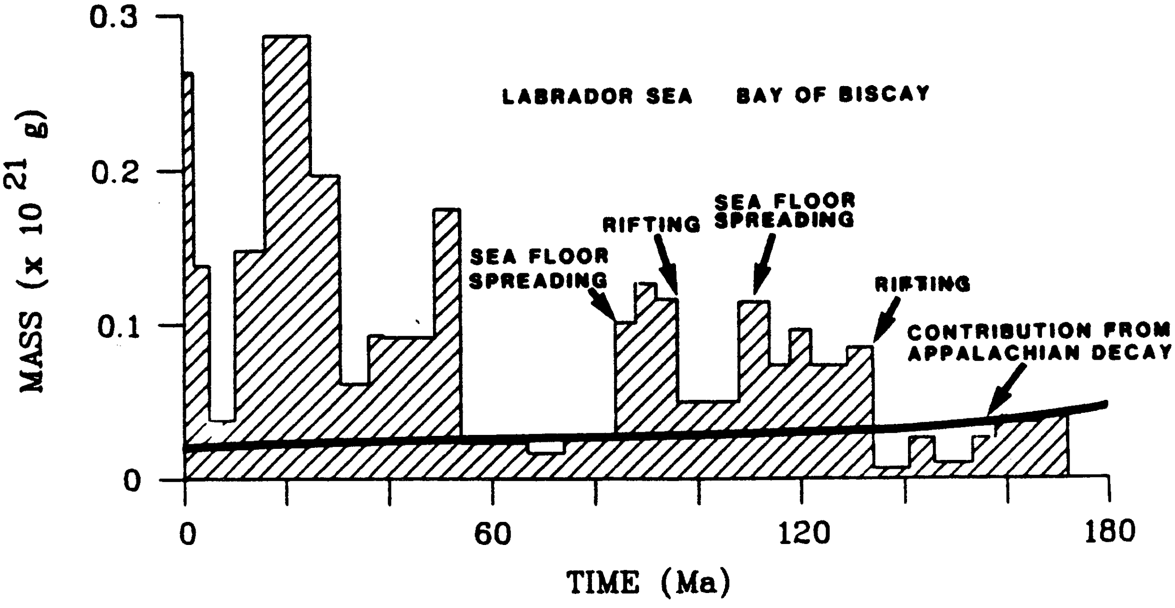
The mass/age distribution of Cretaceous detrital sediment in the western North Atlantic has been compiled from about 3000 stratigraphic sections representing 1/2 x 1/2 degree squares. The study area extends from the U.S. east coast to the mid-ocean ridge, and from 28°N to 48°N latitude. Most of the compilation is based on seismic sections and have poor stratigraphic resolution, recognizing only seven units from Jurassic to Recent. Fine stratigraphic resolution available from Jurassic to Recent, was projected into the data from seismic sections to produce the final mass/age distribution. The Cretaceous detrital sediment in the Western North Atlantic shows two episodes when the mass of sediment far exceeds that expected from the decay of the Appalachians, between 133 and 110 Ma and between 95 and 85 Ma. The excess sediment must come from additional sources(s) Greenland, Iberia and Europe as potential source areas. As shown in the figure below, the first episode, from 133 Ma to 110 Ma may be directly associated with the rifting occurring in the Bay of Biscay and Newfoundland Basin during the Valanginian. The second episode, beginning at 95 Ma and lasting until 85 Ma corresponds to the time of rifting on the site of the Labrador Sea. Sediment fluxes to the western North Atlantic Appalachians. The detrital sediment flux between 110 Ma and 95 Ma is about twice what would be expected from the Appalachians, and implies an external source. The abrupt decreases in sediment flux at 110 Ma and 85 Ma correspond to the times of active sea floor spreading in the Bay of Biscay-Newfoundland Basin and Labrador Sea regions respectively.



# ISOTOPIC VARIABILITY IN MAASTRICHTIAN FRESHWATER BIVALVES: A MEASUREMENT OF ENVIRONMENTAL CHANGE ON WEEKLY, MONTHLY AND YEARLY TIME SCALES

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In order to characterize intra- and inter-annual temperature variations in late Cretaceous continental settings, a freshwater bivalve (*Rhabdotophorus aldrichi*?) from the Hell Creek Formation at Snow Creek, Montana, was microsampled for stable isotope analysis using a computer-controlled X-Y-Z translation stage. Patterns of shell growth were first digitized from a thin-section photograph, and computerized interpolation then allowed sampling of successive 20µm layers precisely parallel to growth banding. Shell aragonite was drilled from areas averaging 25µm in width, 50µm in depth, and 4 mm in length allowing for the removal of up to 60 samples per year of growth, and providing a record of $\delta^{18}O$ and $\delta^{13}C$ variation with a weekly time resolution.

Total variation in the 2.5 years of shell growth sampled is -7.3 to -10.5$^o/_{oo}$ $\delta^{18}O$ (PDB). High frequency $\delta^{18}O$ variation of 0.5$^o/_{oo}$ probably reflects temperature change averaged over 2 to 10 days. Although $\delta^{18}O$ shell aragonite varies in response to changes in both temperature and freshwater isotopic composition, environmental interpretations are possible through comparison with patterns observed in modern Unionid bivalves from Huron River, Michigan. Major foliation in the shell shows a pattern of cloudy shell material followed by clearer growth zones, a growth pattern identical to modern Unionidae. In both, the most $^{18}O$ enriched carbonate immediately precedes cloudy growth layers suggesting that shell growth cessation represents cold weather dormancy or *shutdown* events.

The amplitude of $\delta^{18}O$ variation, therefore, is interpreted as a minimum estimate of change in annual temperature. While warm temperature would result in fluvial water $^{18}O$ enrichment due to evaporation or change in rainwater composition, carbonate would trend toward more depleted values in response to temperature fractionation effects. These antipathetic effects would diminish the amplitude of $\delta^{18}O$ variation such that measured values represent a conservative estimate of intra-annual temperature change. We therefore interpret the 3.25$^o/_{oo}$ variation in $\delta^{18}O$ as reflecting a seasonal temperature variation no less than 13°C. Superimposed on this pattern of $\delta^{18}O$ variation, is an abrupt —2.85$^o/_{oo}$ shift directly following cold temperature shutdown requiring an influx of depleted fluvial waters as growth resumed. Based on comparisons with $\delta^{18}O$ patterns in modern bivalves, we tentatively interpret this shift as a record of snow melt runoff during the spring months.

# PALEOCLIMATIC AND OCEANOGRAPHIC IMPLICATIONS OF CRETACEOUS FAUNAL DISTRIBUTIONS IN THE WESTERN INTERIOR SEAWAY

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A long history of stratigraphic and paleontologic studies coupled with examination of extensive exposures and subsurface data has led to a highly refined biostratigraphic, chronostratigraphic, and geochronologic framework in the Western Interior Basin. This framework makes the Western Interior Basin an ideal laboratory for studying and testing potential relationships between eustacy, oceanographic patterns, biogeography, and climate. However, before relationships and patterns observed in the Western Interior Basin can be adequately compared and related to oceanic or global-scale processes, phenomena largely restricted to this epicontinental basin must be determined and understood. This paper will make observations and comparisons of biogeographic patterns in the Western Interior Basin and elsewhere, as well as discuss problems needing further study.

For example, during the early late Albian transgressive peak, the Gulf Coast reef tract moved further north than during the Late Cretaceous transgressive peaks, but Tethyan and subtropical taxa were more confined to the southern end of the Seaway, apparently because of the restricted nature of its southern aperture. Thus, the Western Interior Basin was more dominated by boreal taxa during the late Albian transgressive highstand than during the Late Cretaceous transgressive peaks when the global climate was probably cooler. Another enigmatic situation is the coincidence of a peak in warm-water Tethyan mollusks in the Western Interior Basin with a period of apparent cooling in the northeastern Atlantic during the early Turonian global transgressive highstand. This discrepancy suggests complex changes in oceanic circulation patterns at that time. On a smaller-scale, the limestone-shale cyclothems associated with peak transgressions in the Western Interior Basin are accompanied by changes in faunal distributions. These faunal fluctuations indicate cycle changes in benthic substrate consistency and oxygenation, providing evidence about the causal mechanisms of the Western Interior cycles and their relationship to sedimentary cycles in the open ocean. In conclusion, our knowledge of the Western Interior Basin and other oceanographic "regions" of the world is becoming refined enough to develop a global picture, but adequate precautions must be taken to sort out regional phenomena.

# MID-CRETACEOUS PHOSPHATIC SEDIMENTS ALONG THE NORTHERN TETHYAN MARGIN: DOCUMENTS OF EXPLICIT NONLINEAR SEDIMENTARY AND ENVIRONMENTAL DYNAMICS

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Phosphorous is an essential element within the biosphere and episodes of large-scale transfer of phosphorous from the biosphere into the geosphere are considered as temporal anomalies in the dynamically equilibrated hydro-geobiosphere system; i.e., phosphatic sediments document dynamic shifts between stable states of this system induced by changes in climatic or tectonic patterns.

The analysis of Lower Aptian to Lower Cenomanian condensed phosphatic sediments along the northern Tethyan margin suggests that the dynamic coupling of the following mechanisms caused excess phosphogenesis (Föllmi, 1989): (1) The predominance of haline-stratified basin waters and conse-quent dislocation of centers of water dynamics onto broad and submerged shelfal areas led to the installation of an important and persistent longshore current system on the northern Tethyan shelf. (2) Nutrient striping by this current system of a well-developed subjacent oxygen-minimum zone coupled with the excess import of terrigenous phosphorous in iron-rich sands induced supersaturation of shelfal bottom waters with respect to phosphate and the proliferation of predominantly suspension-feeding benthic communities, (3) Within the current-induced sedimentary high-energy environment, episodic bypassing of sands dominated patterns of sediment accumulation. Sudden burial of entire benthic assemblages within the event beds resulted in rapid supersaturation of pore waters with respect to phosphate and consequent phosphogenesis. After depletion of internal sources, phosphogenesis was maintained by current-induced convection/diffusion processes of bottom-water phosphates across the sediment/water interface. In episodes of erosion and winnowing, the thus phosphatized particles were concentrated into macroscopic accumulations.

This exceptional coupling of different systems was maintained by shifts in the Aptian climate from relative cool and arid to warm and humid and consequent increase in the deliverance of detrital reactive phosphorous within iron-rich sands (Weissert and Lini in press), by persistent sea-level rises, forcing the current system to remain on the shelf, and by tectonic activism along the northern Tethyan margin, causing a sporadically spasmodic, long-term persistent subsidence of the Tethyan shelf.

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# COMPUTER CLIMATE SENSITIVITY STUDIES OF MILANKOVITCH-SCALE INSOLATION VARIATIONS ON THE CRETACEOUS WESTERN INTERIOR SEAWAY

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Rhythmic sedimentation patterns observed within the Cretaceous Western Interior Seaway, such as those in the Bridge Creek Member of the Greenhorn Formation exposed near Pueblo, Colorado, appear to be a response to episodic climate change. These climatic variations could, in turn, be forced by the periodic insolation change over the North American continent created by Milankovitch-scale Earth-Sun orbital relationships —eccentricity (100 Ky), obliquity, (41 Ky) and precession of the equinox (date of perihelion-23 Ky). Differential heating may have produced air circulation and precipitation changes over the Seaway, which created the conditions that produced the sedimentation patterns.

To test the sensitivity of Cretaceous climate to changes in Milankovitch-scale insolation forcing, a series of simulations were conducted with the National Center for Atmospheric Research's Community Climate Model. Using 100 Ma Cretaceous paleogeography, July and January 300-day simulations were conducted contrasting JULMAX25 (July perihelion, 0.05 eccentricity, 25° obliquity) insolation forcing with JANMIN22 (January perihelion, 0.01 eccentricity, 22° obliquity) insolation forcing. The January JULMAX25 forcing simulation showed increased precipitation over the Western Interior Seaway, which is probably related to increased frequency of passage of low-pressure systems over the northern margin of the Tethys Ocean. This conclusion is supported by statistically significant differences between the means of surface temperature, low-level wind vectors and precipitation, as well as an analysis of storm track passage over the area.

Additional simulations were conducted to determine the effect of removing all sea ice from the model and of varying only the obliquity parameter. The January JULMAX25 simulation maintaining the Arctic Ocean surface temperature at or above 0°C produced minimal change in the North American climatic variables when compared with the January JULMAX25 simulation containing Arctic sea ice. The January JULMAX22 and JANMIN25 simulations, when contrasted with January JULMAX25 and JANMIN22 simulations, suggest that observed rhythmic sedimentation patterns are related to precession of the equinox and eccentricity insolation forcing, rather than to obliquity insolation forcing.

# CIRCUM-ANTARCTIC PALEOBIOGEOGRAPHY OF CAMPANIAN-MAASTRICHTIAN FORAMINIFERA: IMPLICATIONS FOR PALEOGEOGRAPHIC AND PALEOCEANOGRAPHIC RECONSTRUCTIONS

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Paleobiogeographic analysis of southern high-latitude planktonic and benthic foraminifera has revealed Antarctic land-sea distributions, oceanic surface gyre configurations, and changes in the positions of the Tethyan, Transitional, and Austral Realms during Campanian-Maastrichtian time. Poleward changes in the diversity of total and keeled planktonic species of the Southern Hemisphere are compared for the early and late Campanian and early and late Maastrichtian. Latitudinal diversity gradients were weakest during the early Campanian and more pronounced during the late Campanian and Maastrichtian time periods. Shallow marine seaways within West Antarctica are suggested by the similarity of Late Cretaceous nearshore benthic and open ocean planktonic assemblages from southern high-latitude land and deep-sea drill sites, and the occurrence of recycled Cretaceous marine microfossils at Antarctic interior and continental margin localities. Development of a major water mass boundary between cool surface waters south of about 50°S paleolatitude and warmer surface waters to the north in the South Atlantic and Indian Ocean may have caused biogeographic isolation of Austral Realm assemblages during late Campanian and early Maastrichtian time.

Several planktonic foraminiferal species show significant diachroneity in their latitudinal distributions. Magnetobiostratigraphic correlations suggest that *Abathomphalus mayaroensis* migrated from high to low latitudes, whereas *Pseudotextularia elegans, Globigerinelloides subcarinatus, Globotruncanella citae, Globotruncanella petaloidea, Globotruncana bulloides,* and *Globotruncana subcircumnodifer* made time-transgressive poleward migrations. The distribution of *A. mayaroensis* supports isotopic evidence for late Maastrichtian climatic cooling, while that of *P. elegans* correlates with a latest Maastrichtian warming event (about 66.8–66.6 Ma). Delayed first occurrences of the other taxa cannot be explained by paleoclimatic factors alone; variations in global eustatic sea-level and orogensis between southern South America and West Antarctica may have also influenced the taxonomic composition of circum-Antarctic foraminiferal assemblages.

# PALEOGEOLOGY OF THE CRETACEOUS AND ITS IMPLICATIONS FOR CARBON DIOXIDE AND CLIMATE

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The geology of Cretaceous to Recent weathering environments has been reconstructed using published paleolithological maps. This has been done in an effort to assess the climatic significance of changes in the types and distributions of rocks being weathered in the past; such changes might affect carbon dioxide consumption rates and thus $CO_2$ levels. The resulting maps have been rotated to their paleogeographic configurations and gridded at the NCAR CCM scale, so that weathering rate calculations could be made using CCM-derived runoff values (in collaboration with E. Barron).

There is an impressive uniformity through time in the relative aerial proportions of the various rock types exposed globally from Cretaceous to Recent. However, the geographical time, and the total area of exposure has increased (due to eustatic sea-level fall). In particular, the area of low-latitude limestone exposure was much reduced in the Cretaceous; indeed, many of the limestones exposed at low-to-mid latitudes today were deposited about the margin of Tethys during the Cretaceous.

The reduced total, and limestone, exposure area implies that Cretaceous chemical denudation rates might have been lower than those of today. However, continental rainfall and thus runoff appears to have been higher. Limestone weathering does not consume $CO_2$, and thus the higher proportion of low latitude silicate rock exposures might have conspired with increased runoff to ensure that $CO_2$ consumption rates equalled the presumed higher, volcanic Cretaceous $CO_2$ emission rates.

# THE EARTH'S OCEAN CRUSTAL PRODUCTION, 0–150 M.Y.: EVIDENCE FOR A MID-CRETACEOUS "SUPER PLUME"

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A calculation of ocean crust volume as a function of time for the past 150 m.y. reveals a 65–95% increase in ocean crust formation rate from 120 to 80 m.y. This "pulse" in ocean crust production is seen in both spreading rate increases from ocean ridges and in the age distribution of oceanic plateaus. It is primarily a Pacific Ocean phenomenon with an abrupt onset, and peak production rates occurred from 120 to 100 m.y. The pulse then tapered gradually to 80 m.y. when rates dropped significantly but continued to decrease gradually from 80 to 50 m.y. with a secondary production peak near the Cretaceous-Tertiary boundary. For about the past 50 m.y., ocean crust has formed at a "normal" rate. Because the pulse is asymmetric as described above, is seen primarily in the Pacific, and coincides with the long Cretaceous normal magnetic polarity interval (from 118 to 84 m.y.). I interpret it as a "super plume" that originated about 120 m.y. ago near the core/mantle boundary, rose convectively through the entire mantle and erupted beneath the mid-Cretaceous Pacific Basin. The present-day South Pacific "super swell" under Tahiti is probably the nearly exhausted remanent of the original eruption. How this supler plume inhibited magnetic field reversals for 34 m.y. is a matter of speculation, but perhaps heat loss associated with the plume reduced the temperature and raised the viscosity of the outer portion of the Earth's outer core by significant amounts. This in turn reduced its ability to maintain the type of turbulent flow necessary to initiate field reversals until a more normal temperature gradient was restored in the Late Cretaceous.

# PALEOGEOGRAPHIC DISTRIBUTION OF LATER HAUTERIVIAN-EARLY BARREMAIN SEQUENCES OF NEUQUEN BASIN, ARGENTINA

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Data from 31 surface sections and oil industry boreholes were used in a regional sequence stratigraphic study supported by ammonite biochronology of the Late Hauterivian-Early Barremian Agrio Formation (Mendoza Group) in the Neuquén Basin, western central Argentina. As a result, it can be demonstrated that the sedimentological record was not continuous, and different separated depositional events related to third order eustatic oscillations have been recognized. Large segments of the shelf accumulated a monotonous alternance of thin unfossiliferous shales and skeletal-ooidal packstones-grainstones with sharp base and hardground top. Reconstruction of successive paleogeographies reveal a westerly migration of the depocenter in which the trend is characterized by a retraction in the shelf extent of the sequences, the appearance of toplap configurations, and the presence of sigmoidal prograding geometries.

# PALEOCEANOGRAPHY AND PALEOCLIMATOLOGY OF THE CRETACEOUS WESTERN INTERIOR SEAWAY: MARRIAGE OF FORAMINIFERAL PALEOECOLOGY AND CLAY MINERALOGY

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Rocks of the Greenhorn Cyclothem (Kauffman, 1977) were examined for clay mineralogy and foraminiferal content at two localities representing the southwestern part of the Cretaceous Greenhorn Sea. Lohali Point (LP) is located in the eastern Black Mesa Basin of northeastern Arizona and represents a neritic depositional setting. Mesa Verde (MV) is located along the northern rim of the San Juan Basin of southwestern Colorado and represents a proximal basin depositional setting. Marine shales and mudstones of the Mancos Shale were studied. Both sections are underlain by the Dakota Sandtone. The Greenhorn sequence at LP (203.2 m) is capped by the Toreva Sandstone. The sequence at MV (141.6 m) is capped by several thin Semilla-equivalent sandstones and the Juana Lopez Member of the Mancos Shale. This sequence spans the upper Cenomanian —upper middle Turonian and records the greatest flooding of the Western Interior during Cretaceous time (T1-R1 of Molenaar, 1983).

A third short section through the lower Bridge Creek Member of the Greenhorn Formation at Rock Canyon (RC; Pueblo, Colorado) serves as a distal basin site for comparison with the LP and MV sections. Detailed analyses across the Cenomanian-Turonian boundary interval at all three localities show that the most proximal (LP) and most distal (RC) sites contain very similar faunal and clay mineral trends while MV differs in fundamental ways. We attribute these differences primarily to source area and paleocirculation/watermass differences. An abundance of chlorite and illite at MV may indicate a different, perhaps more northerly source for the clays. LP and RC appear to have been influenced by warm, stratified water masses from the south associated with approach of peak transgression based on the occurrence of diverse assemblages of upper Cenomanian (*S. gracile* ammonite zone) planktonic foraminifera including *Rotalipora*. In addition, both of these sections show a marked increase in *Heterohelix* at the base of the uppermost Cenomanian *N. juddii* ammonite zone. We interpret the increase in *Heterohelix* as reflecting a major expansion or incursion of an oxygen-minimum zone into the southern Western Interior Seaway. *Rotalipora* is absent and the increase in *Heterohelix* is much more subtle at MV. Paleocirculation patterns or mixing may have disrupted the northward incursion of southerly watermasses in the vicinity of MV.

In the broader picture of the entire Greenhorn sequence, the LP and MV sections contain very similar patterns in clay mineralogy. The major clay mineral differences between the two sections are the presence of chlorite at MV and its absence at LP, and the greater relative percentages of illite at MV. The most striking feature of both sections is the marked dominance of kaolinite associated with peak transgression of the Greenhorn Sea (upper *M. nodosoides* -lower *C. woolgari* ammonite zones). The relative abundances of kaolinite are greater in the more proximal LP section, with the exception of the peak transgression interval where LP and MV have virtually identical proportions of kaolinite. This interval also corresponds with the greatest influx of subtropical molluscs into the seaway. We propose that regional climate became wetter with the northerly incursion of warm water masses deep into the core of the seaway. A warmer, wetter climate facilitated the chemical weathering of alumino-silicate rocks and minerals resulting in a greater production of kaolinite. Retreat of subtropical water masses with regression reduced the chemical weathering potential and with it a marked decline in the production of kaolinite in terrestrial environs adjacent to the seaway.

# FINE-GRAINED SEDIMENT DISPERSAL ALONG THE WESTERN MARGIN OF THE CRETACEOUS INTERIOR SEAWAY, SOUTHERN UTAH

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Decoding the record of *temporal* changes in Cretaceous climates, ocean circulation, and paleogeography as recorded in fine-grained, marine sediments should be based on an understanding of the *spatial* variablity associated with fine-grained sediment dispersal systems, and of the processes by which that sediment was transported and accumulated. Recently, a number of investigations of modern, fine-grained sediment dispersal systems that are associated with moderate to large-sized fluvial sources, and that debouch into both pericontinental and epicontinental seas, have been conducted. This research has greatly expanded our knowledge of the processes and products of such systems, and these data provide a critical foundation on which to base interpretations of Cretaceous mudstones.

This poster presents some of the results of an ongoing study of fine-grained sediment dispersal recorded in the Turonian Tununk and Tropic Members of the Mancos Shale, which accumulated near the western, tectonically active margin of the Cretaceous Western Interior Seaway of North America. Bentonite layers, previously identified and correlated by Zelt (1985), have been used to study time-equivalent facies in both shore-parallel and shore-normal transects. The shore-normal transect extends up to 130 km from the shoreline toward the center of the Seaway. In a seaward direction, trends in relative sediment accumulation rates, assessed by comparing the stratigraphic thicknesses of mudstone between bentonite layers, point to the existence of a subaqueous delta, which prograded eastward during the study interval. This subaqueous delta resembles features identified in well logs by Asquith (1970), elsewhere along the margin of the Seaway. Time-equivalent facies of this subaqueous delta resemble those found on modern deltas of the Amazon and Huange rivers.

In the Tununk/Tropic shale muddy sediments interpreted as topset deposits grade abruptly seaward from thick beds of physically stratified sandstone of the inner shelf. The fine-grained sediments are composed of moderately to pervasively bioturbated, clayey siltstone interbedded with event layers composed of ripple-cross-laminated and parallel-planar-laminated coarse silt. In general, the event layers thin and the muddy "background" sediment fines in a seaward direction. Sediment transport calculations, presented in this poster, and based on a wave-current interaction model, provide estimates of the magnitude of the storm-wave- and storm-current-generated boundary shear stresses that resulted in deposition of the coarse event layers, and of the gradient of offshore decrease in these shear stresses. Foreset sediments in the Tununk/Tropic shale ar markedly thicker (accumulated more rapidly) than the topset and bottomset deposits and are characterized by well-laminated to sparsely bioturbated silty claystone and clayey siltstone. Laminae are generally parallel, and apparently represent fluctuations in the character of suspended sediment deposition. Those Tununk/Tropic sediments that accumulated on the bottomsets are clayey siltstone and coarse siltstone heterolith, which shows evidence of a moderate degree of bioturbation and of periodic reworking by southward, basin-axial (shore-parallel) currents capable of transporting coarse silt as bedload. Sediment transport calculations are presented to estimate the shear stresses produced by such flows, and corresponding near-bed velocities.

Detailed study of mudstone facies in vertical sequences reveals trends consistent with previous interpretations that the Tununk and Tropic shales were deposited during a time of transgression and then regression. Within the generally regressive upper parts of the succession, however, evidence for a minor transgression is indicated by an omission surface marked by a thin lag of shell debris and an abrupt fining of sediments. After this transgression, the regressive trend resumed. Trends in grain size and in physical and biogenic sedimentary structures within the two stacked, regressive packages suggest that they comprise two vertically stacked deltas that built seaward during two successive, relative highstands of sea level.

# STRATIGRAPHIC, PETROLOGIC, AND PALEONTOLOGIC EVIDENCE FOR A BRACKISH, RESTRICTED SEAWAY IN EARLY CENOMANIAN (MID-CRETACEOUS) TIME, EASTERN WYOMING

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Unusual, concretion-bearing mudrocks of late early Cenomanian age, which might indicate a restricted embayment of the Cretaceous epeiric sea, have been recognized at outcrops in eastern Wyoming and in adjoining areas of Montana, South Dakota, Nebraska, and Colorado. In south-central Johnson County, Wyoming, these rocks are in the lower part of the Frontier Formation and are about 34 m (110 ft.) thick; they consist of medium- to dark-gray, noncalcareous, silty shale and clayey or sandy siltstone, and light-gray to grayish-red bentonite. The shale and siltstone are either bioturbated or interlaminated; laminae are discontinuous, parallel, and even or wavy. Burrows are common but comprise only a few taxa. Throughout the region, these beds contain sparse arenaceous foraminifers, but no macrofossils. The concretionary strata are conformably underlain by the lower Cenomanian(?) Mowry Shale and are conformably overlain by lower (?) and middle Cenomanian siliciclastic rocks in the lower to middle part of the Frontier Formation.

In studies of a drill-core from south-central Johnson County, the lower part of the Frontier was divided into the following units, in ascending order: unit 3, mainly shale; unit 2, mostly concretion bearing mudrocks; and unit 1, mainly clastic rocks. The composition of unit 2 contrasts significantly with that of the underlying and overlying units. The matrix of unit 2 contains no pyrite or dolomite and much less sulfur than units 1 and 3. Unit 2 also includes sideritic and calcitic concretions, whereas units 1 and 3 contain neither concretions nor siderite and only sparse calcite. Carbon-sulfur-iron chemistry for the mudrocks and concretions in unit 2 suggests that low sulfate availability limited sulfide formation. The isotopic values for carbon and oxygen in the sideritic and calcitic concretions are much lower than those of most Cretaceous marine limestones and suggest cementation during early diagenesis in a variety of microenvironments.

When considered in conjunction with the proportions of sulfur, organic carbon, and iron in unit 2, the major-element, isotopic, and paleontologic data suggest that the waters of the southern part of the late early Cenomanian epeiric sea were brackish to fresh and oxic. The low salinity of this part of the sea might have been caused by high meteoric runoff from the adjoining lowlands and by an abnormal constriction in the seaway north of Montana.

Rates of precipitation estimated for this part of the Western Interior during the mid-Cretaceous are unusually high.

The mudrocks of units 3 and 2, and of a lower part of unit 1, accumulated in a boreal sea at low to moderate rates of sedimentation in association with generally weak current or wave action. Units 3, 2, and 1 record a marine regression and a subsequent marine transgression during early and middle Cenomanian time. Tectonism in western Wyoming during the late Albian and early Cenomanian, as well as a eustatic fall in the early Cenomanian, could have caused the regression, whereas a eustatic rise in the middle Cenomanian probably caused the transgression and the development of the Late Cretaceous epicontinental seaway.

# CRETACEOUS NON-MARINE CLIMATE RECONSTRUCTION, WITH EMPHASIS ON POLAR REGIONS

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Most quantitative information on Cretaceous temperatures is derived from marine rocks and fossils, in particular, from oxygen isotopic data. However, although the latitudinal gradients derived from marine temperature data are useful for a general understanding of global tempertures and for understanding the temperature structure of the oceans and seas themselves, they are not a good proxy for continental climates. This may be particularly true for the Cretaceous; some numerical simulations of Cretaceous climate have resulted in highly seasonal (with respect to temperature) continental interiors and steep coastal temperature gradients, especially during the winter. Thus, information on temperature and precipitation gathered from terrestrial deposits is crucial to understanding not only continental climates, but also the dynamics of global climate.

Cretaceous floras in northern Alaska are Cenomanian, Coniacian, and late Campanian-Maastrichtian age. Throughout this interval, the vegetation was a mixed-coniferous forest with an understory of angiosperms and ground cover of ferns and horsetails. However, diversity of the flora decreased dramatically by the late Campanian-Maastrichtian suggest that temperature may have played a larger role in limiting plant growth during the later interval, whereas the winter decrease in light triggered dormancy in the Cenomanian.

The Cenomanian Dunvegan Formation in northeastern British Columbia also contains a diverse flora and bears a close physiognomic resemblance to the coeval flora in Alaska. Unlike the Alaskan flora, however, the Dunvegan flora contains evergreen elements among the angiosperms. In addition, no well-preserved fossil wood has been found; this prevents not only the climatic interpretations that are made possible by growth-ring analysis, but also a confident assessment of the importance of the angiosperms in the canopy. Nevertheless, the presence of evergreens among the angiosperms suggests that winter temperatures were not severe. Mean annual temperature probably was in the range 12-16°C, depending on whether the angiosperms constituted canopy or understory.

# THE CRETACEOUS SOUTH ATLANTIC LAKES AND THEIR WATER SOURCE

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Rifting between South America and Africa resulted in the production of basins that held fresh water lakes in which large masses of organic carbon accumulated and playa lakes in which salts accumulated. The lake basins were the result of differential stretching along the margin between Recife-Niger and the Torres syncline-Cabo Frio. The stretching was maximal where the margin was perpendicular and minimal where the margin was parallel to the stretching-spreading direction. The deepest basins formed where the margins were perpendicular to the stretching-spreading direction. Although stretching along the South American and African margins often involved the formation of half grabens, and the detailed distribution of these features is propriety and not available to us, a simple model assuming equal stretching of the margins at half the initial spreading rate yeilds a useful approximation of the size and shapes of the lake basins. There is dispute in the literature as to whether there were one, two or possibly more lakes that existed along the rifting margins. The model suggests that early in the rifting process a number of basins were formed that may have held lakes. As rifting proceeded, these coalesced to form the major lakes, called Lagoa Feia on the Brazilian and Lake Bucomazi on African margin. At their greatest extent, the lakes could have been 1500 km long, 300 km wide, and 2.5 km deep. The lakes lay in the arid zone, which readily explains why they sometimes became playas. Fresh water lakes of this size required a major source of water. The only adequate source would have been the equatorial rain belt centered on the paleoequator, which at 130 Ma lay at about the latitude of Recife-Niger (McElhinney, 1973, paleomagnetic reference frame) or Guinea Plateau-Sinai (Harrison and Lindh, 1982, paleomagnetic reference frame). The equatorial rain belt would have migrated with the monsoonal circulation and would have received larger amounts of precipitation, which would have been fed to the rift by a river occupying Benue trough. The river connecting the earlier lakes must have flowed from north to south and emptied into the ocean across Walvis Ridge-Rio Grande Rise.

# CRETACEOUS PLATE TECTONIC REORGANIZATIONS: MECHANISM FOR GLOBAL CHANGE

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Nine plate tectonic reconstructions are presented illustrating the changing configuration of the continents and ocean basins during the Cretaceous. The data used to produce these maps were compiled as part of the PALEOMAP Project, International Lithosphere Program. These Cretaceous reconstructions are a synthesis of the regional plate tectonic models produced by individual working group members (Atlantic: Srivastava, Müller, Klitgord, Cande; Indian: Royer, Patriat; Pacific: Atwater, Stock; Asia: Rowley; Tethys: Sengor, Dewey; Circum-Antarctic: Lawver).

The orientation and paleolatitudes of the continents was determined by using paleomagnetic data and by back-tracking the motion of the plates along hot spot tracks. A Global Apparent Polar Wander (APW) path has been constructed by compiling reliable paleomagnetic data for the major continents (Van der Voo) and then rotating them into "reconstructed" coordinates using the global plate model. A comparison of plate motions derived from hot spot tracks (Müller) with the predictions from paleomagnetism suggests that the African and Indian hot spots have remained nearly fixed with respect to the spin axis, since the mid-Cretaceous.

An analysis of plate motions during the Cretaceous indicates that long intervals of nearly steady-state plate motion were interrupted at irregular intervals by global tectonic "events" during which there was a major change in plate motion. Continent-continent collisions, or the subduction of major spreading centers may have been the principal causes of these global plate tectonic reorganizations. During the Cretaceous, the major global tectonic events occurred at 140–130 Ma (Berriasian - Valanginian), at 95–85 Ma (Cenomanian - Santonian), and at 75–65 Ma (Campanian-Maestrichtian). Several secondary events can also be resolved.

We believe that these major global tectonic events may have been an underlying cause for global changes in climate, sea-level, ocean circulation, and primary productivity during the Cretaceous.

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