# CRETACEOUS WESTERN INTERIOR SEAWAY DRILLING PROJECT: AN OVERVIEW

WALTER E. DEAN[1] AND MICHAEL A. ARTHUR[2]

[1]*U.S. Geological Survey, Federal Center, Denver, Colorado 80225*

[2]*Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802*

ABSTRACT: The Cretaceous Western Interior Seaway Drilling Project was begun in 1991 under the auspices of the U.S. Continental Scientific Drilling Program. It was intended to be a multidisciplinary study of Cretaceous carbonate and siliciclastic rocks in cores from bore holes along a transect across the Cretaceous Western Interior Seaway. The study focuses on middle Cretaceous (Cenomanian to Campanian) strata that include, in ascending order, Graneros Shale, Greenhorn Formation, Carlile Shale, and Niobrara Formation. The transect includes cores from western Kansas, eastern Colorado, and eastern Utah. The rocks grade from pelagic carbonates containing organic-carbon-rich source rocks at the eastern end of the transect to nearshore coal-bearing units at the western end. These cores provide unweathered samples and the continuous depositional record required for geochemical, mineralogical, and biostratigraphic studies. The project combines biostratigraphic, paleoecological, geochemical, mineralogical, and high-resolution geophysical logging studies conducted by scientists from the U.S. Geological Survey, Amoco Production Company, and six universities.

## INTRODUCTION

### *What Is the Cretaceous Western Interior Seaway Drilling Project (WISDP)?*

The U.S. Continental Scientific Drilling Program (CSDP) was established in 1988 when Congress passed the Continental Scientific Drilling and Exploration Act (P.L.100-441) mandating that three U.S. Government agencies, the Department of Energy (DOE), the U.S. Geological Survey (USGS), and the National Science Foundation (NSF), develop long- and short-term policy objectives and goals for scientific drilling in the United States. Representatives from these agencies comprise the CSDP Interagency Coordinating Group (ICG/CSDP), which provides multiyear, multihole scientific research strategies for the CSDP. In 1990, we proposed to the ICG/CSDP to drill a transect of cores across the Cretaceous Western Interior Seaway (WIS) that extended from the Gulf of Mexico to the Arctic during maximum marine transgressions (Fig. 1). The proposed transect was to consist of four holes or groups of holes from western Kansas, eastern Colorado, southwestern Colorado, and eastern Utah. We proposed to focus on the two most extensive transgressive episodes in the seaway during the middle Cretaceous that resulted in deposition of two important organic-carbon-rich pelagic limestone units, the Cenomanian-Turonian Greenhorn Formation and Santonian-Campanian Niobrara Formation. An interdisciplinary team of researchers from government, academia, and industry would conduct biostratigraphic studies, paleoecologic studies, inorganic, organic and stable isotopic geochemical studies, mineralogical investigations, and high-resolution geophysical logging. Cores would provide the unweathered samples and continuous smooth exposures required for these studies.

The needs for the eastern end of the transect were met by a hole that was drilled and continuously cored with better than 90% recovery by Amoco Production Company in western Kansas (Amoco No. 1 Rebecca K. Bounds, Greeley County, Kansas; Fig. 2). The Cretaceous part of this core is archived in the USGS Core Research Center (USGS-CRC) in Denver. The 450-m Cretaceous section recovered in the Bounds core extends from the top of the Upper Jurassic Morrison Formation to the middle of the Upper Cretaceous Niobrara Formation (Fig. 3) (Dean et al., 1995).

The needs for the western end of the transect were met in 1991 when the USGS drilled and continuously cored three holes, all about 300 m deep, with better than 98% recovery in the Kaiparowits Basin of south central Utah (Fig. 2). Two holes (USGS-CT1-91 and USGS-SMP1-91) were drilled on top of the Kaiparowits Plateau to collect the coal-bearing sequences of the Upper Cretaceous Straight Cliffs Formation (Hettinger, 1995). A third hole (USGS No. 1 Escalante) was drilled at the base of the Kaiparowits Plateau near the town of Escalante, Utah, and collected all of the marine Tropic Shale and the top of the Dakota Sandstone (Fig. 4). The cores from these three holes are archived in the USGS-CRC in Denver.

During June 1992, the USGS, with DOE funding, drilled and continuously cored a 213-m hole (USGS No. 1 Portland; Fig. 2) in Cretaceous strata east of the Florence oil field in the Cañon City Basin near Florence, Colorado. Core recovery was essentially 100% and includes the lower half of the Niobrara Formation, all of the Carlile Shale, Greenhorn Formation, and Graneros Shale, and the top of the Dakota Sandstone (Fig. 5). Of particular note was the excellent recovery of very distinct limestone-marlstone cycles of the Greenhorn and Niobrara. Both of these pelagic carbonate units contain abundant marine organic matter that may be sources of petroleum in the Florence field as well as in the Denver basin.

The fourth site of the original transect in the northern San Juan Basin of southwestern Colorado was not drilled because the section there was collected by M. R. Leckie and colleagues in a series of trenches along the northern boundary of Mesa Verde National Park (Fig. 2) (Leckie et al., this volume). The results presented in this volume are mainly based on cores from the other three points along the transect (Bounds, Portland, and Escalante cores; Fig. 2), but data are presented from other cores that are publicly available in the USGS-CRC, Denver, from several outcrop sections, and from the Leckie et al. trench (Fig. 2).

### *Why the Cretaceous?*

The Cretaceous Period (ca. 142-65 Ma) of earth history offers a significant opportunity for understanding global processes and their variations. Cretaceous marine and terrestrial strata are extremely widespread in outcrop, subcrop, and in ocean basins. Many of the subcrop sections are recoverable by shallow to

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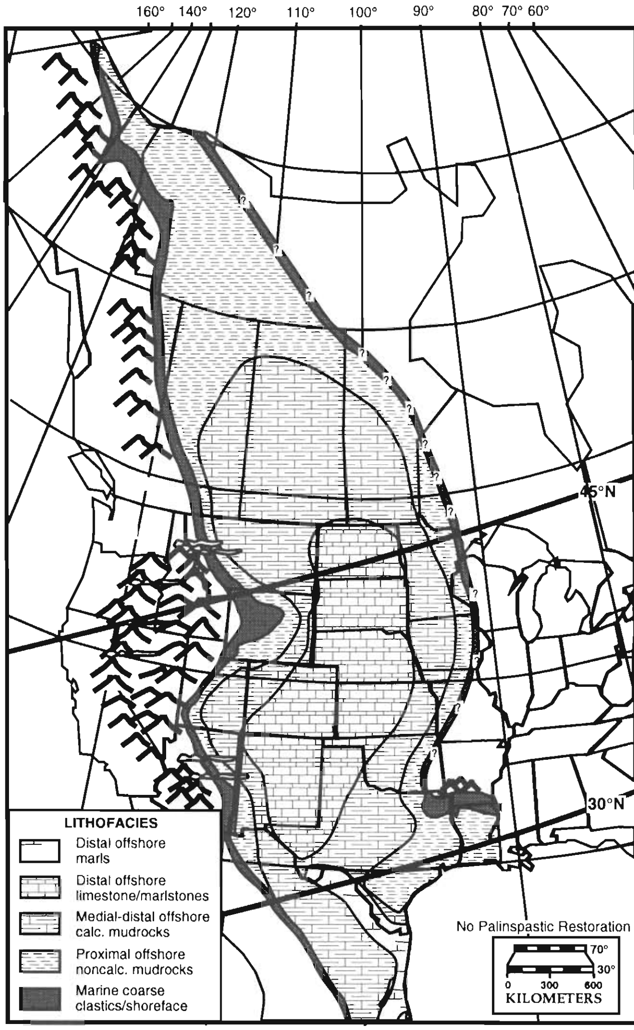


FIG. 1.–Lithofacies map for the early Turonian of the Western Interior Seaway. Paleolatitude lines at 30° and 45°N also are shown. Modified from Sageman and Arthur, 1994.

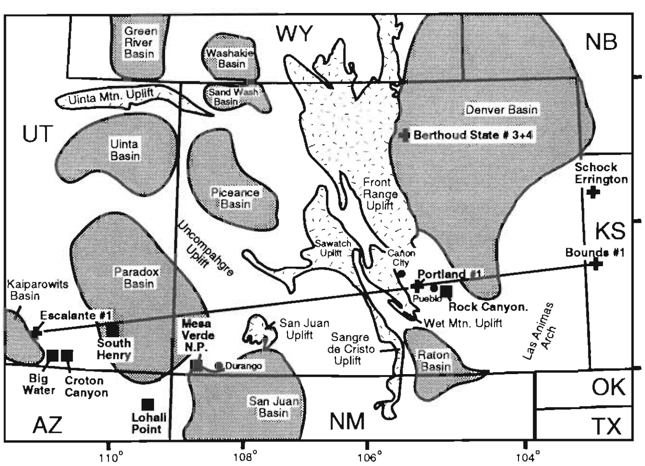


FIG. 2.–Map showing locations of major basins and uplifts in Colorado and adjacent states, locations of cores described in this volume (plus symbols), and locations of outcrop sections discussed in this volume (solid squares).

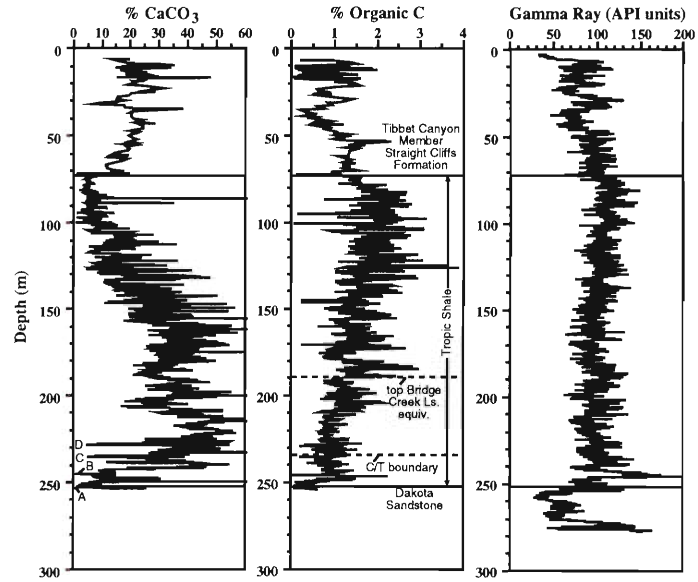


FIG. 3.–Plots of percentages of $CaCO_3$ and organic carbon in the Tropic Shale and lower part of the Tibbet Canyon Member of the Straight Cliffs Formation in the USGS No. 1 Escalante core. The position of the Cenomanian/Turonian (C/T) boundary and the top of strata equivalent to the Bridge Creek Limestone Member of the Greenhorn Formation also are shown.

intermediate (up to 1000 m) continental drilling and ocean-basin sites are accessible by deep-sea drilling. Variable combinations of tectonism, volcanism, atmospheric and ocean chemistry, climate, sea level, and sediment supply helped to produce some of the largest phosphorite deposits and hydrocarbon reserves known on earth (Fig. 6). It is estimated that Cretaceous source rocks are responsible for more than 70% of the world's reserves of crude oil (Tissot, 1979). Understanding the origin and distribution of Cretaceous, organic-rich sequences is tantamount to understanding the origin and distribution of much of the world's oil and gas. In addition, Cretaceous strata contain major reserves of coal, kaolinite, bauxite, and manganese. Accurate prediction of the availability of such resources, and an understanding of their distribution requires models based on a comprehensive knowledge of the Cretaceous world.

The Cretaceous is marked by substantial changes in the extent of shelf and epicontinental seas and in regional and global patterns of marine sedimentation. These changes were the result of major fluctuations in global eustatic sea level (Haq et al., 1987) (Fig. 7). Much of the Cretaceous is also recognized as having had a globally warm, equable, mostly ice-free climate that is about as far removed from our present glacially dominated climate as that of any other time in the Phanerozoic. The origins of this warm climate are not well understood, but are presumed to be related to a major "greenhouse" phenomenon, which possibly was the result of increased volcanic outgassing of carbon dioxide (e.g., Arthur et al., 1985b and 1991; Lasaga et al., 1985).

The middle Cretaceous between 120 Ma and 80 Ma (Aptian to Campanian) is characterized by several globally widespread episodes of organic-carbon burial in marine sequences (e.g., Schlanger and Jenkyns, 1976; Arthur and Schlanger, 1979; Jenkyns, 1980; Arthur et al., 1987; Schlanger et al., 1987; Arthur et al., 1990). These episodes represent periods of widespread

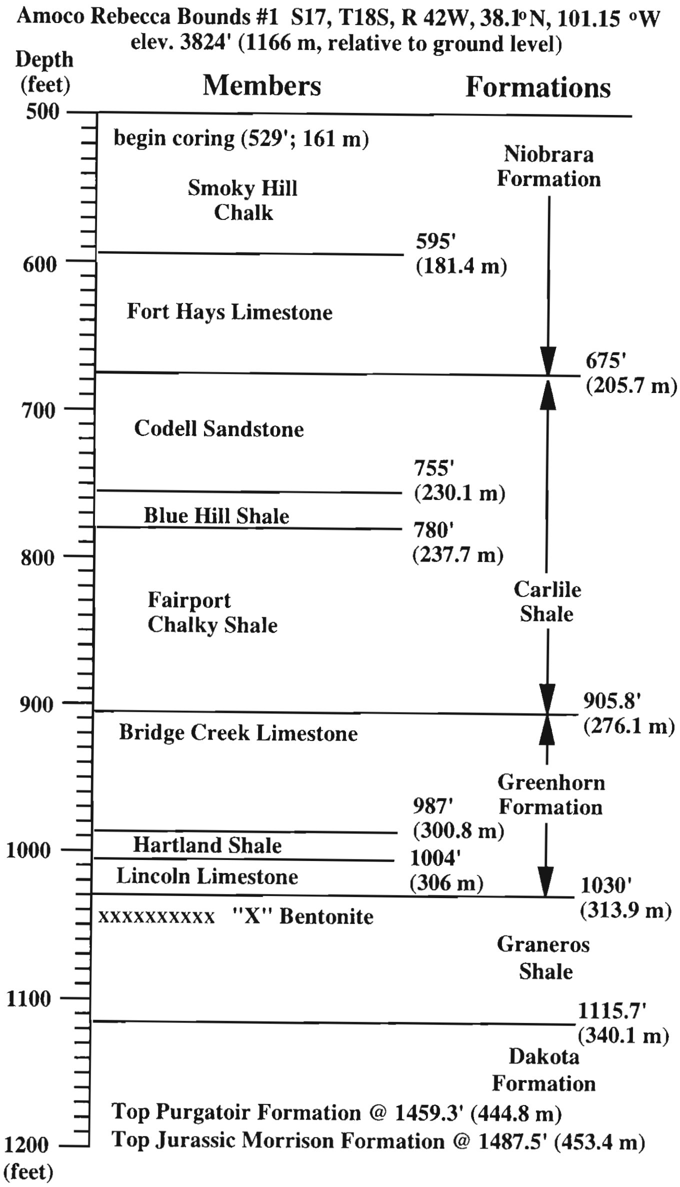


FIG. 4.–Depths to tops of formations and members recovered in the Bounds core.

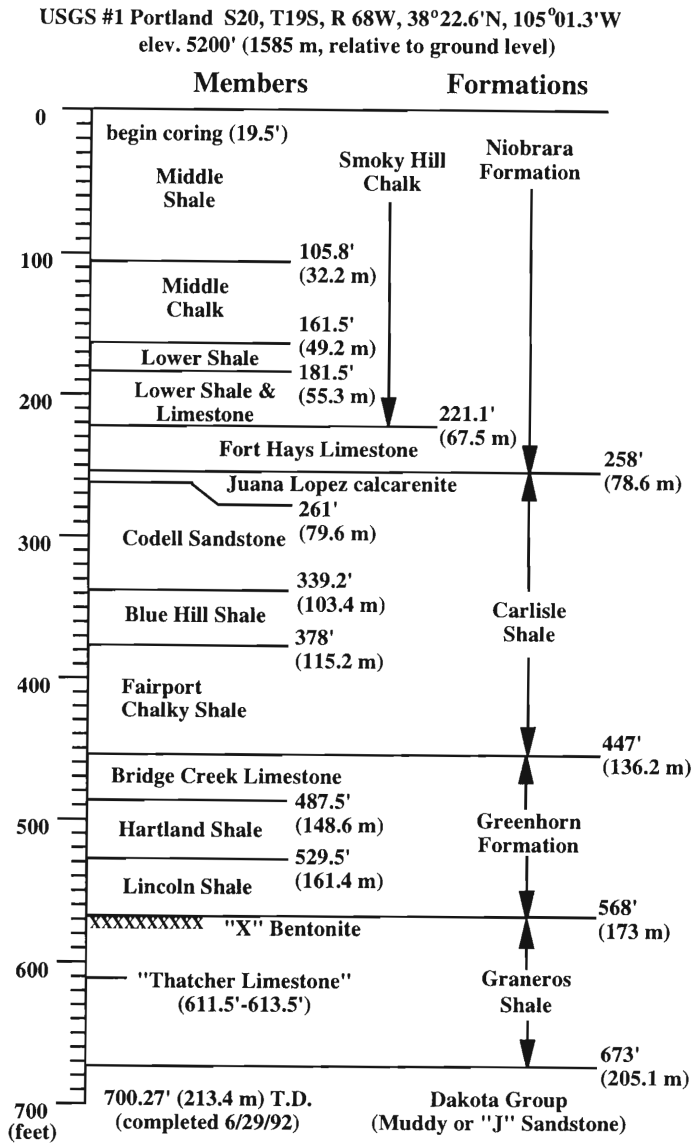


FIG. 5.–Depths to tops of formations and members recovered in the Portland core.

oxygen deficiency in oceanic mid- and deep-water masses that have been termed "Oceanic Anoxic Events" (OAEs; Fig. 7). The widespread occurrence of OAEs in time and space within the middle Cretaceous may imply fundamental changes in oceanic circulation and (or) the rate and mode of delivery of organic matter to the deep sea. The origins of the OAEs are not known for certain, but available data suggest that such events resulted from some combination of higher phytoplankton productivity and enhanced preservation under oxygen-depleted, deep-water masses. Arthur and Natland (1979) suggested that the injection of warm, saline water produced in marginal evaporite basins around the Atlantic during the middle Cretaceous may have created a stable salinity stratification and periodic anoxia in the deep Atlantic. Brass et al. (1982) concluded that the main effect of a warm, saline deep-water mass on oxygen concentration would be through reduced oxygen solubility in warmer water. Herbert and Sarmiento (1991) pointed out that a warm, saline deep-water mass would also increase the efficiency with which plankton extract nutrients from convecting waters at low latitudes. Sarmiento et al. (1988) produced a more broadly applicable 3-box model for the widespread and rapid formation of deep-water oxygen deficits by varying the rate of supply of organic matter to the deep water relative to rate of supply of oxygen to deep water from high-latitude, oxygen-bearing surface water. Jewell (1996), using a three-dimensional ocean circulation model, determined that the surface-water residence time of the seaway was 0.6 to 2.5 years whereas that of deep water (<100 m) was 1.3 to 4.6 years. Because of the short deep-water residence time, apparent oxygen utilization was modest for all simulations that Jewell tried. Anoxic episodes that occurred in the Cenomanian/Turonian WIS apparently were the result of incursions of mid-depth, suboxic to anoxic waters from the open ocean, or restricted deep-water circulation due to a sill at the entrance to the seaway. Slingerland et al. (1996) used a three-dimensional, turbulent-flow, coastal-ocean model to estimate circulation and chemical evolution of the seaway. This model showed that drainages from the eastern margin were more important than previously suspected and created a strong counterclockwise gyre that was effective in mixing

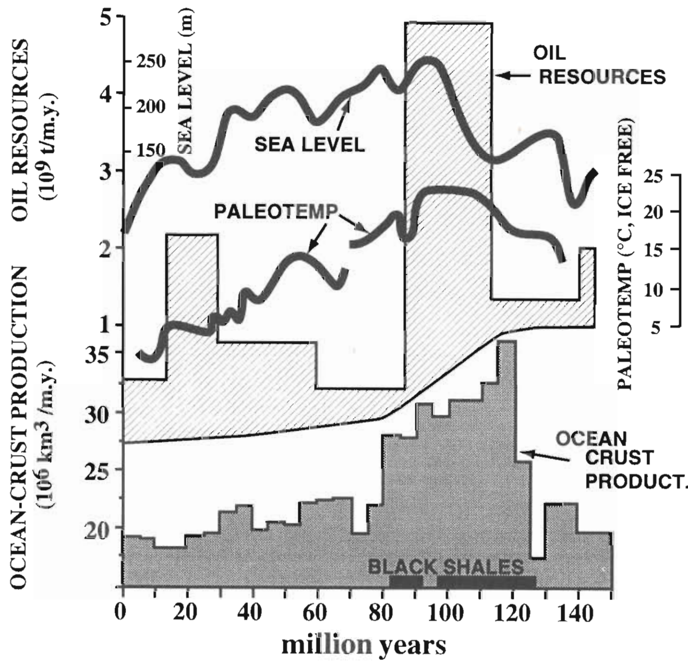


FIG. 6.–Combined plot of world ocean crust production (modified from Larson, 1991a), high-latitude sea-surface temperatures (Savin, 1977; Arthur et al., 1985b), long-term eustatic sea level (Haq et al., 1988), times of black shale deposition (Jenkyns, 1980), and world oil resources (Irving et al., 1974; Tissot, 1979) plotted on geologic time-scale of Harland et al. (1982). Modified from Larson, 1991b.

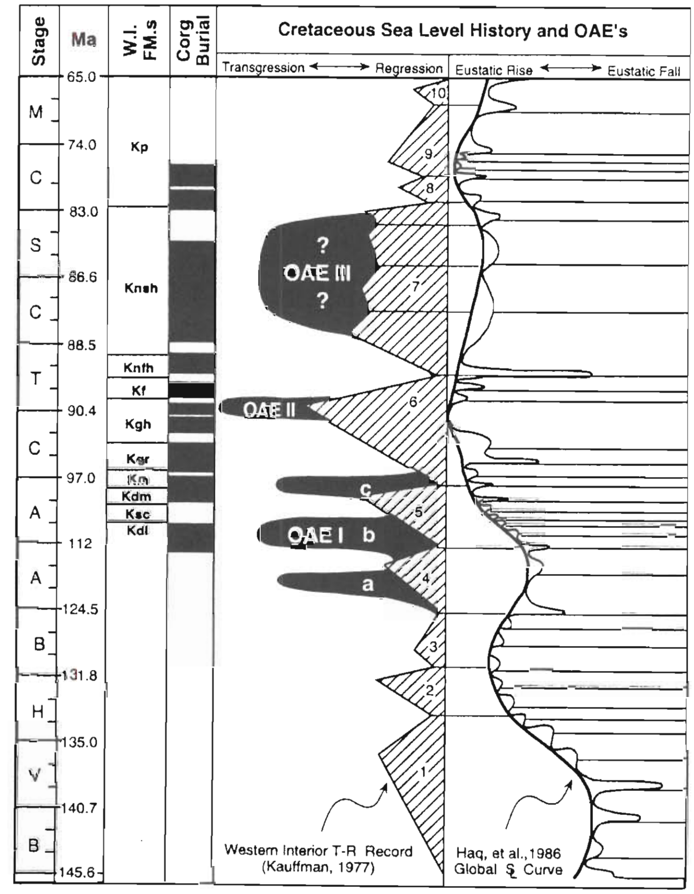


FIG. 7.–Global sea-level history compared with transgressions and regressions and development of organic-carbon-rich deposits in the Western Interior Seaway. The global sea-level curve of Haq et al. (1987) is correlated to transgressions and regressions of the Western Interior Seaway compiled by Kauffman (1977). Major sequence boundaries are correlated to regressive maxima by solid lines. Black bars mark stratigraphic intervals with high levels of preserved organic carbon (Corg>2%). Oceanic Anoxic Events (OAE) intervals are from Arthur et al. (1990). Western Interior Cretaceous formations (W.I. FMs) include: Kp=Pierre Shale; Knsh= Smoky Hill Chalk Member of the Niobrara Formation; Knfh= Ft. Hays Limestone Member of the Niobrara Formation; Kf= Fairport Shale; Kgh= Greenhorn Formation; Kgr= Graneros Shale; Km=Mowry Shale; Kdm=Muddy Sandstone Member of the Dakota Formation; Ksc=Skull Creek Shale Member of the Dakota Formation; Kdl=Lytle Sandstone Member of the Dakota Formation. Stage abbreviations, from top to bottom, are: M=Maastrichtian; C=Campanian; S=Santonian; C=Coniacian; T=Turonian; C=Cenomanian; A=Albian; A=Aprian; B=Barremian; H=Hauterivian; V=Valanginian; B=Berriasian. Ages of stage boundaries are from Harland et al. (1982).

Tethyan and boreal waters. These studies, however, do not comprehensively explain the interplay between climate, sea level, surface- and deep-ocean circulation, and organic-carbon production and burial.

### *Why the Western Interior Seaway?*

The U.S. Western Interior Seaway (WIS) extended from the Gulf Coast to the Arctic during maximum Cretaceous transgressions as a northwestern arm of the Tethys Ocean (Fig. 1). The numerous energy-rich Cretaceous foreland basins of the Rocky Mountain regions of North America are the remnants of this once extensive seaway. Cretaceous sequences in the WIS are an important part of the global expression of high eustatic sea levels, tectonism, warm climate, and oxygen depletion because of the relative geographic isolation of the seaway and, therefore, its strong susceptibility to paleoclimatic and paleoceanographic change (e.g., Kauffman, 1977 and 1984; Barron et al., 1985). The WIS sequences are renowned for their expression of small-scale cyclicity, with periods of tens to hundreds of thousands of years that commonly are attributed to Milankovitch orbital variations (Fischer, 1980 and 1993; Arthur et al., 1984; Fischer et al., 1985; Bottjer et al., 1986; ROCC Group, 1986; Pratt et al., 1993; Dean and Arthur, this volume; Sageman et al., this volume; Scott et al., this volume). However, the linkages of these presumed orbital variations to sedimentary processes in a supposed ice-free world are poorly understood in contrast to Quaternary cycles with similar periodicities. The WIS sequences provide a tremendous opportunity to examine the sedimentary expression of orbital cyclicity in a geographically restricted part of the Cretaceous ocean that apparently was finely tuned to these orbital variations.

Two important organic-carbon-rich pelagic limestone units were deposited in the eastern part of the WIS during the two most extensive transgressive episodes (e.g., Kauffman, 1977; Arthur et al., 1985a; Pratt et al., 1993). The Cenomanian-Turonian transgression resulted in deposition of the Bridge Creek Limestone Member of the Greenhorn Formation (OAE II, Fig. 7), and the Late Turonian through early Campanian transgression led to sedimentation of the Niobrara Formation (OAE III, Fig. 7). Both of these pelagic carbonate units were deposited in a rapidly subsiding basin (Bond, 1976; Cross and Pilger, 1978) that was characterized by substantial clastic sediment input (e.g., Ryer, 1977a and b) from uplifted tectonic terranes of the Sevier orogenic belt to the west (Armstrong, 1968; Weimer, 1970) as well as an abundant supply of windblown ash from volcanic activity in the same region (Kauffman, 1977). At maximum transgression, the shoreline of the WIS extended as far west as western Utah and western Arizona (Fig. 1). The predominantly pelagic carbonate units of Kansas and eastern Colorado are replaced by a more clastic-rich sequence in western Colorado and eastern Utah. Important coal-bearing sequences equivalent in age to the Niobrara were deposited along the western shoreline in Utah, and were cored as part of the WISDP (Hettinger, 1995). In the northern San Juan basin in southwestern Colorado, the Niobrara equivalents are represented by sandstones of the lower Mesa Verde Group, and the upper part of the Mancos Shale, and the time equivalent of the Greenhorn Formation is the lower Mancos Shale (Fig. 8). We have selected these time intervals, which represent extremes in global eustatic sea level and resulting continental flooding, to test the sensitivity of ocean circulation to global climatic forcing as the result of the changing configuration of continental topography and shallow seas.

The Cretaceous sequences of the Western Interior are among the most studied in the world. Knowledge of the Western Interior, built up over the years by industry, government, and academic scientists, provides exceptional temporal and spacial control for working out sequence stratigraphic relationships, and provides extensive knowledge on the sedimentology, geochemistry, paleontology, and paleobiology of these sequences. The temporal control is the most precise of any Cretaceous sequence in the world, both in terms of absolute radiometric ages (Obradovich, 1993) and high-resolution biostratigraphic zonation (Kauffman et al., 1993; Scott et al., this volume). The extensive paleogeographic, stratigraphic, biotic, and geochemical data available for Cretaceous strata in the WIS suggests that an understanding of the response of a large epicontinental sea to variations in global forcing is within our grasp. This knowledge can then be extended to less explored foreland basins of the world that have similar sequences. Our approach focuses on the middle Cretaceous marine record of the WIS and the extent to which marine sedimentation in the seaway reflects global events at various times. For example, with respect to so-called "anoxic events", many workers favor models that involve propagation of external marine environmental conditions, especially oxygen-deficient deeper water masses, into the WIS as the result of global eustatic sea level rise with a superimposed imprint of regional environmental conditions (e.g., Fischer and Arthur, 1977; Barron et al., 1985; Arthur et al., 1987; Glancy et al., 1993). Others hypothesize that the WIS and equivalent depositional environments on other continents are the sources of global oxygen-deficient mid- to deep-water masses (e.g., Eicher and Diner, 1989; Fisher et al., 1994). These contrasting hypotheses are amenable to testing by modeling efforts tied to comprehensive data syntheses and model validation.

Because the Cretaceous is so important to so many different disciplines of the geosciences, the Global Sedimentary Geology Program (GSGP) identified "Cretaceous Resources, Events and Rhythms" (CRER) as its first major international project (Ginsburg and Beaudoin, 1990). Under this project are five Working Groups: (1) Sequence stratigraphy and sea level change; (2) Black shales and organic-carbon burial; (3) Cyclostratigraphy; (4) Carbonate platform evolution; and (5) Paleogeography, paleoclimatology and sediment fluxes. Marine sedimentary units deposited in the Cretaceous WIS provide an exciting opportunity to develop and integrate the five working group themes listed above in one project. The results of east-west WISDP transect described in this volume address the objectives of all of the CRER working groups except those of the carbonate platform working group. We hope that a future WISDP north-south transect will include sections of carbonate platforms in New Mexico, Texas, and Mexico. The strata of interest monitor global change during the Cretaceous and include a number of petroliferous units; are characterized by well-developed cyclicity in the Milankovitch band; pose a variety of interesting paleoclimatic, paleoceanographic and sediment flux problems; and are dominated by sequences produced by marked transgressive-regressive cycles. The following sections describe how the WISDP is addressing the objectives of the working groups of CRER.

## OBJECTIVES OF WESTERN INTERIOR SEAWAY DRILLING PROJECT

### *Sea Level Change and Sequence Stratigraphy*

The WISDP transect provides sampling of strata deposited during two major transgressive-regressive cycles of the WIS that reflect global changes in sea level (Figs. 6, 7). The origin of these sea-level changes is puzzling because much of the Cretaceous is thought to have been ice-free and characterized by warm, latitudinally equable climates and, therefore, ice-volume changes could not have induced much variation in sea level. On the other hand, the Cretaceous was a time of unusually active seafloor spreading, with plate-margin and mid-plate volcanism so extensive that tectonically induced changes in sea level should be expected, possibly corresponding to thrust loading on the western edge of the basin.

Key objectives are: (1) to determine the precise timing and rates of sea-level change and their influence on lithology, sedimentation rate, and sediment geochemistry; (2) to determine the amount, type, and degree of preservation of organic matter and its relation to sea-level variations, whether tectonic or eustatic. (3) to examine rates of subsidence, apparent sea-level change, and facies migration in light of purported global tectonic-eustatic events.

### *Organic Matter Deposition and Burial*

The cored sequences on the WISDP transect encompass several episodes of enhanced burial of organic carbon that are important both within the WIS and globally. These periods of widespread oxygen deficiency in oceanic deep-water masses (so-called "Oceanic Anoxic Events"; Fig. 7), marked by widespread organic-carbon-rich sequences loosely called "black-shales," include several hydrocarbon source-rock sequences as well as economically important coal sequences (Sageman and Arthur, 1994).

Key objectives are: (1) to determine onshore-offshore facies patterns and relationships of organic-matter accumulation, changes in organic-matter type and degree of preservation, and how these relate to transgressive episodes; (2) to use variations in faunal and floral components and sedimentary structures to evaluate the extent and intensity of oxygen deficiency during black-shale episodes and correspondence in timing to global events; (3) to determine the effects of organic-matter enrichment on the geochemical characteristics of the sediments, particularly as they relate to the cycling of Fe, Mn, S, P, and trace elements; and (4) to determine the effects of thermal metamorphism and other geochemical characteristics with increasing burial depth along the transect of cores using the fresh, unweathered samples that the cores provide.

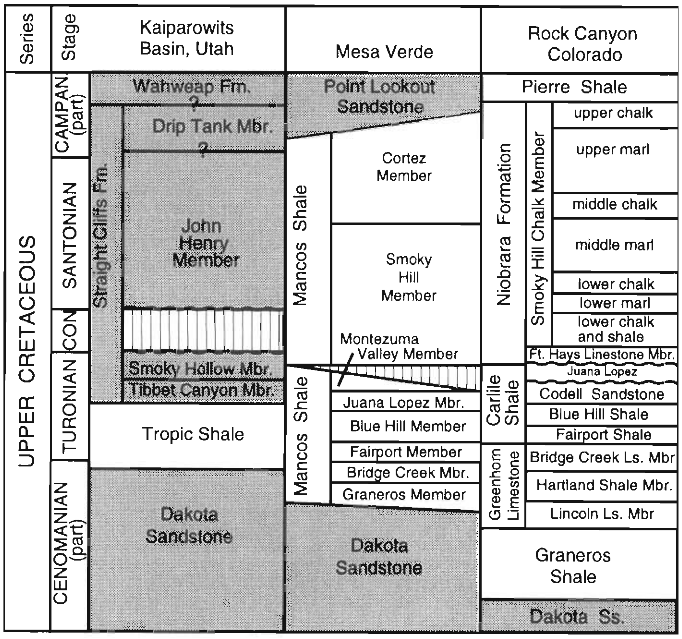


FIG. 8.–Stratigraphic columns showing correlation of stratigraphic units from Rock Canyon near Pueblo, Colorado, Mesa Verde, Colorado, and the Kaiparowits Basin, Utah. Modified from West and Leckie (this volume). White panels represent units of fine-grained carbonate or mud rocks; shaded panels represent sandstone units; panels with vertical stripes represent lacunas.

### *Cyclostratigraphy*

The Cretaceous sequences of the WIS are renowned for their expression of small-scale cyclicity, with periods of tens of thousands of years that commonly are attributed to Milankovitch orbital variations (Gilbert, 1895; Hattin, 1971 and 1985; Kauffman, 1977; Fischer, 1980; Pratt, 1981; Arthur et al., 1984; Barron et al., 1985; Barlow and Kauffman, 1985; Bottjer et al., 1986; ROCC Group, 1986; Pratt et al., 1993). In addition, longer-term cycles with periodicities of up to several million years, are defined on geochemical and geophysical logs (Arthur and Dean, 1992; Pratt et al., 1993; Dean and Arthur, this volume) and also may be related to orbital cycles or possibly to sea level changes that are correlated with Milankovitch forcing. However, the linkages of these presumed orbital variations to sedimentary processes in a supposed ice-free world are poorly understood in contrast to ice-volume-dominated Quaternary cycles with similar periodicities. The continuously cored sequences and high quality geophysical logs of the WISDP transect provide a tremendous opportunity to examine the sedimentary expression of orbital cyclicity in a geographically restricted part of the Cretaceous ocean that apparently was finely tuned to these orbital variations. In addition, the sequences of the WIS contain the greatest diversity of faunal and floral assemblages of any Cretaceous sequence in the world.

Key objectives are: (1) to use the detailed biostratigraphies provided by the faunal and floral assemblages, with abundant volcanic ash layers, to provide a unique, high-resolution time sequence for precisely calibrating cyclicity; (2) to use these "absolute" age data to calculate important variables such as rates and timing of sediment supply, organic productivity, and changes in water-mass characteristics that contribute to the sedimentary expression of Milankovitch orbital cycles.

### *Paleogeography, Paleoclimatology, and Sediment Fluxes*

The origins of the warm climate of the Cretaceous are poorly understood, but are presumed to be related to a major expression of a greenhouse phenomenon, such as might result from increased volcanic outgassing of carbon dioxide. However, even the warm, equable climate paradigm is being challenged – at least for some parts of the Cretaceous – as new data are obtained. The WIS sequences of the North America are an important part of the global expression of high eustatic sea levels, tectonism, warm climate, and oxygen depletion because of the relative geographic isolation of the seaway and, therefore, its strong susceptibility to paleoclimatic and paleoceanographic change.

Key objectives are: (1) to relate trends in geochemical properties and organic-carbon accumulation rates to global sea level, tectonism, warm climate, and oxygen depletion; (2) to provide validation of climate models (e.g. GCMs); (3) to provide explanations for the significance of bioevents and substantial changes in global biotic diversity during the Cretaceous; (4) to document rates and timing of biotic extinction and evolution in detail; (5) to investigate the possibility that shallow Cretaceous seas such as the Western Interior Seaway were the sources of oxygen-depleted oceanic deep-water masses and anoxia.

## SUMMARY OF RESULTS

Scott et al. provide a chronostratigraphic reference section for the upper Albian (Purgatoire Formation) to Coniacian (Fort Hays Member of the Niobrara Formation) for western Kansas based on detailed graphic correlation of paleontological data (dinoflagellates, foraminifera, calcareous nannofossils, pollen, spores, and molluscs) from the Bounds core. The Bounds reference section is linked to key reference sections in Europe and North Africa by graphic correlation. Scott et al. then use the chronology produced by the Bounds reference section to define four orders of cycles. The longest cycles are parasequences of 2.0 to 3.4 My in duration represented by the Purgatoire Formation, the lower Dakota Formation, the upper Dakota and Graneros Formations, and the Greenhorn and Carlisle Formations. The shortest cycles with periodicities of tens of thousands of years occur in the Greenhorn Formation and are best displayed by the striking limestone/marlstone cycles in the Bridge Creek Limestone Member of the Greenhorn. Using their graphic correlation chronology, Scott et al. concluded that the 13 cycles in the Bridge Creek in the Bounds core, which average 1.5 m in thickness, have an average duration of 17,333 years, very close to the 19,000 and 21,000 Milankovitch orbital precession cycles.

Numerous investigators during the last century, beginning with G. K. Gilbert (1895), have tried to refine the timing of the carbonate cycles in the Greenhorn Formation, as well as those in the Niobrara Formation, and several papers in this volume, in addition to Scott et al., address this issue. Another hotly debated aspect of these cycles is their origin. Because of the shallow depths of the Western Interior Seaway, carbonate dissolution can be ruled out as the primary cause, but arguments have been made both for and against carbonate production and clastic dilution as the primary cause. Burns and Bralower examined assemblages of calcareous nannofossils and carbon and oxygen isotopic composition of the fine fractions (<38mm) of these two carbonate units in the Bounds and Portland cores to see if they could distinguish between carbonate production and clastic dilution. They found that despite the shallow water depths during deposition of these carbonate units, there is considerable variability in the preservation of calcareous nannofossils. The best preserved nannofossils are in the Niobrara Formation in the Bounds core, and the worst preserved are in the Niobrara Formation in the Portland core. Preservation of nannofossils in the Bridge Creek Limestone is moderate in both cores. Variations in abundances of nannofossil fertility indicators do not correlate with those in carbonate content, which suggests that the cyclic lithologic variations may not be associated with surface-water conditions. Values of $\delta^{18}O$ of the fine-fraction carbonate also do not correlate with carbonate content, but they are negatively correlated with abundances of species of these calcareous phytoplankton that are thought to indicate of high surface-water fertility. This suggested to Burns and Bralower that surface-water fertility was higher when runoff of freshwater from the western highlands was greater, which brought in more detrital clastic material, and freshwater with lower values of $\delta^{18}O$. They conclude, therefore, that the limestone/marlstone cycles in the Bridge Creek and Niobrara appear to be controlled by both carbonate production and clastic dilution.

Bralower and Bergen describe the calcareous nannofossil assemblages in 1100 samples from the Cenomanian to Santonian sections in the Bounds, Portland, and Escalante cores. Based on this biostratigraphy, they correlated the Cenomanian/Turonian boundary between cores and with an outcrop section in southern Utah. However, other stage boundaries could not be correlated. Also, there is a discrepancy in the stratigraphic position of the Cenomanian/Turonian boundary between western, marginal sections and basin-center sections, probably due to one or a combination of environmental factors such as salinity and fertility.

Biostratigraphy and paleoecologic interpretations based on planktonic and benthic foraminifera by West et al. provide an important link between the subsurface (USGS core from Escalante, Utah) and outcrop sections along the western margin of the seaway at maximum transgression in late Cenomanian and early Turonian. Cyclic changes in foraminifera assemblages in the Tropic Shale in the Escalante core and in outcrops of the Mancos Shale at Lohali Point, Arizona, and Mesa Verde National Park, southwestern Colorado (Fig. 2), record dynamic changes in paleoceanography linked to major transgressive-regressive episodes. Relative abundance of the benthic foraminifer *Gavelinella* clearly delimit several of the sequence stratigraphic boundaries of Leithold (1994) in the Tropic and Tununk Shales in southern Utah. Changes in species of benthic foraminifera occur in response to cyclic variations in food and bottom-water oxygenation associated with shifting water masses. At the time of maximum transgression (early Turonian), the seaway was filled with a warm, oxygen-depleted, southerly (Tethyan) water mass. However, the transition from calcareous to agglutinated benthic foraminifera in the middle Turonian suggests that the warm, southern water mass was replaced by a cold, boreal water mass.

Leckie et al. extend the foraminifera interpretations of West et al. for the western margin of the basin eastward toward the center of the basin at the classic section at Rock Canyon near Pueblo, Colorado (Figs. 2, 8). Leckie et al. confirm the findings of West et al.: that the benthic foraminifera assemblages in the Mancos Shale at Lohali Point, Arizona are very similar to those in the Mancos at Mesa Verde National Park, Colorado, and both are different than those in the time-equivalent Bridge Creek Limestone at Rock Canyon. The benthic foraminifera assemblages at Mesa Verde and Lohali Point contain distinct arenaceous taxa with northern affinities. This suggests that a cool, northern bottom-water mass predominated along the western margin of the basin. In contrast, the planktonic foraminifera assemblages at Lohali Point are more similar to those at Rock Canyon than those at Mesa Verde, and suggest a Tethyan source. The clay mineral suites at each of the three sites are dominated by detrital illite and smectite derived from the Sevier orogenic belt to the west. However, the clay mineral suites at Lohali Point and Rock Canyon also contain substantial amounts of kaolinite derived from somewhere other than the Sevier orogenic belt. Because of the similarities in planktonic foraminifera and clay-mineral assemblages in the Cenomanian/Turonian rocks at Lohali Point and Rock Canyon, Leckie et al. conclude that these sites received a southern surface-water mass and a southern detrital source in addition to the dominant detrital influx from the western Sevier region.

Savrda presents the results of careful, detailed analyses of ichnofossil variations in both the Bridge Creek Limestone and Niobrara Formation in the Bounds and Portland cores. Analyses of individual burrowed intervals involved identification of burrow types (to the ichnogeneric level when possible) and assessment of burrow diameters and penetration depths. Within the Bridge Creek Limestone, Savrda identified four ichnocoenoses based on recurring ichnofossil associations. Vertical stacking patterns of ichnocoenoses and laminated intervals (laminites) were then used to reconstruct the histories of paleo-oxygenation. The analyses reveal that paleo-oxygenation progressively decreased during deposition of the Bridge Creek at both core sites. Comparison of interpreted oxygenation curves (IOC) indicates that the floor of the seaway was less oxygenated at the Bounds core site in western Kansas than at the Portland core site in central Colorado, at least during deposition of the clastic-rich parts of bedding couplets. These curves also define high-amplitude redox cycles that correspond to the limestone/marl couplets of the Bridge Creek as well as higher-frequency, lower-amplitude cycles within marlstone and shale units.

For the Niobrara, Savrda used the vertical disposition of six oxygen-related ichnocoenoses and associated laminites to reconstruct oxygenation histories at both sites. As for the Bridge Creek, oxygenation curves indicate a broad trend towards benthic deoxygenation during deposition of the Fort Hays and Smoky Hill Members. Oxygenation cycles of variable amplitude and frequency, which generally correspond to carbonate rhythms, are superimposed upon this trend. Decimeter-scale and lower-frequency cycles in both members may be linked to orbitally forced climate cycles, whereas higher-frequency cycles in the Smoky Hill record periodic or episodic processes operating at time scales shorter than Milankovitch orbital rhythms. Laminated fabrics are more common in the lower Smoky Hill in the Bounds core than they are in the Portland core. This suggests that differences in depositional conditions between the two sites during deposition of the lower Smoky Hill were similar to those during deposition of the Bridge Creek; i.e., benthic oxygenation of the seaway at the Bounds core site was significantly lower than at the Portland core site.

Sageman et al. applied quantitative spectral analyses to lithologic and paleoecologic cycles at the C/T boundary in the Bridge Creek Limestone in the Portland core to determine the dominant periodicities of the cycles. They used a combination of percent carbonate, percent organic carbon, grayscale pixel values from scanned photographs, ichnologic measurements from Savrda (this volume) and nannofossil data from Burns and Bralower (this volume). The analyses were aided by recently published radiometric (Obradovich, 1993) and biostratigraphic data (Kauffman et al., 1993). Spectra of percent $CaCO_3$, percent organic carbon, and grayscale pixel values produced significant periodicities that closely approximate the three major Milankovitch cycles of eccentricity, obliquity, and precession in the upper 6 m of the Bridge Creek Limestone. Spectra for maximum burrow diameter and oxygen-related ichnocoenosis rank are similar to those for percent organic carbon, which suggests a common control by bottom-water oxygenation. Spectra for some calcareous nannofossil taxa are less definitive due to poor preservation. Sageman et al. then developed a new model for causes of cyclicity in the Bridge Creek Limestone in which obliquity controlled dilution by terrigenous clastic material through its effects on precipitation at high latitudes. This dilution also brought in fresher water, resulting in stratification of the water column, lower benthic oxygen levels, better preservation of organic matter, and less bioturbation, the classic dilution-redox model for the WIS cycles. On the other hand, cyclic fluctuations in carbonate production are mainly controlled by evaporation and nutrient upwelling in the Tethyan realm south of the WIS. The two forcing mechanisms mix in the shallow seaway to produce the complex bedding patterns observed in the Bridge Creek Limestone.

Pancost et al. used hydrocarbon biomarkers and compound-specific carbon isotope analyses at the Cenomanian/Turonian boundary interval in the Bounds, Portland, and Escalante cores to try to detect trans-basinal variations in organic matter input and diagenesis. As expected, the influx of terrestrial organic matter was greatest along the western margin (Escalante core). Marine contributions were greatest in the central basin (Bounds and Portland cores). The organic matter in the Bounds core is enriched in $^{13}C$ relative to that in the Portland core, which Pancost et al. interpret as indicating that the seaway at the site of the Bounds core in Kansas was dominated by warm, $CO_2$-poor, Tethyan waters, whereas the seaway at the site of the Portland core in Colorado, the seaway was dominated by $CO_2$-rich, boreal waters. The isotopic composition of the isoprenoid hydrocarbons pristane and phytane suggests that greater selective degradation of marine organic matter and (or) lower marine productivity occurred during deposition of the limestone beds relative to the marlstone beds.

The upper Cenomanian to middle Turonian Tropic Shale, and the correlative Tununk Shale Member of the Mancos Shale, accumulated along the western margin of the Western Interior Seaway in Utah. From studies of these units in outcrops and southern Utah and in the Escalante core, Leithold and Dean conclude that these units record relatively rapid deposition in prodeltaic environments. Detailed examination of primary sedimentary structures, ichnofabric, and fecal pellets suggest that sediment accumulation in this setting was the result of both suspension fallout from river plumes and storm-induced turbidity currents. Carbon burial in the deltaic deposits was apparently affected by global, regional, and local processes. In the lower part of the Tropic Shale in the Escalante core, for example, a marked positive carbon isotopic excursion near the Cenomanian/Turonian boundary parallels that seen at many localities around the world. In the Tropic Shale, however, unlike in other Cenomanian and Turonian successions, peak concentrations of marine organic matter are not observed at the boundary but stratigraphically higher. In the Escalante core, an upward trend toward increasing concentration of hydrogen-rich, marine organic matter parallels evidence both for progressively increasing sediment accumulation rates and for decreasing oxygen levels.

Changes in paleoceanographic conditions across the Cenomanian/Turonian boundary in the Tropic Shale in the Escalante core were investigated by Pagani and Arthur, who measured major and trace elements and carbon and oxygen isotopic composition of the carbonate in bulk samples, inoceramids, and ammonites. Stable isotopic compositions of well-preserved shell carbonate derived from inoceramids and ammonites reflect temporal and spatial environmental variations within the water column. Inoceramid oxygen-isotopic compositions are probably influenced by "vital effects" and do not appear to directly record primary conditions. However, temporal trends in inoceramid isotopic values probably reflect relative environmental variations. Negative shifts in ammonite $\delta^{18}O$ coincide well with short-term, base-level cyclicity. The amplitude of these negative shifts is interpreted to reflect the influence of two distinct water masses. A freshened, northern component water with a depleted $\delta^{18}O$ signature is closely associated with the western boundary of the basin and dominates during regressive events and (or) progradation of the shoreline. This agrees with results of previous studies of planktonic organisms (e.g., West et al., this volume) as well as with recent numerical circulation models for the WIS.

Cyclic variations on scales of decimeters to tens of meters in concentrations of carbonate, detrital clastic material, organic-carbon, and in degree of bioturbation characterize the cyclic pelagic limestone sequences of the Niobrara Formation. Although the cycles in the Niobrara Formation on all scales can adequately be represented as a three-component system of carbonate, clay, and organic carbon, multivariate Q-mode factor analyses of elemental geochemical data by Dean and Arthur identified which other elements are associated with these three components, and also defined several other element associations that reflect more subtle geochemical differences in the Niobrara, due mainly to changes in redox conditions. Biogenic carbonate, windblown volcanic ash, and terrigenous detritus transported by winds, rivers, and surface currents competed against one another during deposition of the carbonate units of the Niobrara. Dean and Arthur attempted to use elemental ratios to try to detect relative changes in influx of detrital illite, volcanic smectite, and eolian quartz. Although they found marked changes in clastic sources with time, they found little difference in the composition of the clastic faction that can be related to individual limestone/marlstone cycles and, therefore, dry/wet climatic cycles. Dean and Arthur used the oxygen-isotope composition of bulk carbonate and concentrations of Mg and Sr to detect evidence for burial diagenesis in the Niobrara. Values of $\delta^{18}O$ in bulk carbonate are about 2‰ lower in the Smoky Hill Member in more deeply buried sections in eastern Colorado than in more shallow buried sections in western Kansas. Most of this difference is due to greater burial diagenesis in Colorado with formation of isotopically light carbonate cements. However, even when corrected for burial diagenesis, the values of $\delta^{18}O$ in the Niobrara are still lower than those in open marine carbonates of the same age (e.g., Austin Chalk), providing further evidence for seawater of lower than normal salinity in the Western Interior Seaway. If the carbonates in the Niobrara underwent burial diagenesis, as suggested by the oxygen-isotope data, then Sr and Mg should have been lost during recrystallization and cementation. However, the observed concentrations of Sr and Mg are remarkably close to those predicted by theoretical mixing lines between their concentrations in pure pelagic biogenic carbonate and Cretaceous clay, suggesting that the carbonates in the Niobrara did not lose Sr or Mg through diagenesis.

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