EVIDENCE FOR MILANKOVITCH PERIODICITIES IN CENOMANIAN–TURONIAN LITHOLOGIC AND GEOCHEMICAL CYCLES, WESTERN INTERIOR U.S.A.

B.B. SAGEMAN1, J. RICH1, M.A. ARTHUR2, G.E. BIRCHFIELD1, AND W.E. DEAN3
1 Department of Geological Sciences, Northwestern University, Evanston, Illinois 60208, U.S.A.
2 Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802, U.S.A.
3 United States Geological Survey, MS 539, Federal Center, Denver, Colorado 80225, U.S.A.

ABSTRACT: The limestone/marble bedding couplets of the Bridge Creek Limestone Member, Cenomanian–Turonian Greenhorn Formation, were analyzed by applying spectral techniques to high-resolution lithologic and geochemical data from a core. The results suggest that the Bridge Creek contains a complex record of orbital cyclicity. The dominant signal appears to be obliquity, but signals corresponding to precession and eccentricity were also observed. The development of the bedding couplets is interpreted to have resulted from a combination of factors, including insolation-controlled changes in higher-latitude precipitation leading to diatom/redoxygen cycles, and in lower-latitude evaporation, leading to changes in surface water conditions and productivity cycles in the calcareous plankton. The data interpreted to reflect redox cycles appear to be more strongly influenced by obliquity, and show a weak precessional signal. In contrast, trends in the carbonate record show the opposite response. The complex bedding pattern observed in the Bridge Creek Limestone is interpreted to result from competing influences of different orbital cycles expressed through different pathways of the depositional system, and was also affected by changes in sedimentation rates related to relative sea level fluctuations, aperiodic dilution by volcanic ash, and changes in organic-matter production and redox conditions related to a global “oceanic anoxic event”. These factors complicate cycle analysis in the lower part of the member but leave a relatively undisturbed record in the upper Bridge Creek Limestone.

INTRODUCTION

Over the last century, since G.K. Gilbert (1895) hypothesized that the rhythmically bedded strata of the Bridge Creek Limestone Member, Greenhorn Formation, in central Colorado represented the sedimentological expression of climate cycles forced by changes in the Earth’s orbit, geologists have sought to document and better understand this phenomenon. Recognizing that the potential to correlate bedding cycles with orbitally forced climate cycles is highest in the relatively continuous sequences of quiet depositional environments, most cyclostratigraphers have focused on rhythmically bedded pelagic and lacustrine deposits. Analyses of Mesozoic pelagic rocks of the Tethyan Realm, particularly those of Aptian through Turonian strata in Italy (Fischer 1980; Fischer et al. 1985; Herbert and Fischer 1986), and more recently in deep sea cores from the Deep Sea Drilling Project and the Ocean Drilling Program (e.g., Dean et al. 1984; Arthur and Dean 1991) have been particularly fruitful. Increasingly sophisticated methods have been applied to the problem of establishing periodicity in these deposits (Park and Herbert 1987), and a number of plausible models to explain the link between climate and sedimentary systems in a greenhouse world have been advanced (R.O.C.C. Group 1986; Arthur and Dean 1991; Pratt et al. 1993). Through the years, however, cyclostratigraphers have consistently returned to the famous Bridge Creek sequence that originally inspired Gilbert (e.g., Fischer 1980; Fischer et al. 1985; Arthur et al. 1985; Kauffman 1988) and lamented that insufficiently resolved chronology and a somewhat chaotic record conspire to prevent a more rigorous analysis of cyclicity in this classic sequence.

In this paper we report evidence of Milankovitch periodicities in the Bridge Creek Limestone Member based on a newly refined chronostratigraphic record for the interval (Obradovich 1993; Kauffman et al. 1993) and the collection of high-resolution data from a core recently drilled in central Colorado (Dean and Arthur 1994). These data include stratigraphic, lithologic, and biogenic variations documented in measured sections and core photographs, and geochemical variations in measured carbonate and organic-carbon content of the rocks. Periodicity in these records was analyzed using spectral techniques by which spatial frequency data were converted to the time domain using sedimentation rates derived from the new cyclostratigraphy. This approach allows us to test for the presence of periodic oscillations corresponding to the astronomical periods for precession (~21 ka), obliquity (~41 ka), and eccentricity (~100 and ~400 ky) in the stratal patterns of the Bridge Creek Limestone Member. Secondly, it allows inferences to be made concerning the sedimentologic mechanisms by which the orbital “clock” is expressed in the rock record, revealing much about the strengths and limitations of that record. Finally, the results provide input to the evaluation of different models for the linkage between climate and depositional systems in the Northern Hemisphere during Cretaceous time.

GEOLOGIC BACKGROUND

The Western Interior Basin (WIB) of North America (Fig. 1) was an Andean-style foreland that developed during Late Jurassic and Cretaceous time in response to crustal loading in the tectonically active Sevier Orogenic Belt (Jordan 1981; Kauffman 1984). During Albian to Maastrichtian time a combination of load-induced subsidence and large-scale tectono-eustatic fluctuations led to a series of marine incursions in the basin, and resulted in development of a meridional seaway during peak sea-level highstands (Kauffman 1977, 1984). The sedimentary records of these marine incursions have durations of 7–10 My and correspond to the second-order sequences of Haq et al. (1987). Each is characterized by dominance of thick siliciclastic sequences on the west derived from the uplifted fold and thrust belt that borders the foreland basin, and by fine-grained carbonate-rich facies on the east, where broad lowlands provided little siliciclastic input (Kauffman 1977, 1984). The Greenhorn cycle was deposited in the WIB (Fig. 2) during the late Cenomanian to early Turonian (C–T). As sea level approached peak highstand for this cycle, a succession of carbonate-rich hemipelagic rocks—the Greenhorn Formation—accumulated in the central part of the basin (Fig. 1). This region includes the bathymetrically deepest part of the seaway, and estimated depths for peak Greenhorn highstand are 200–300 m (Sageman and Arthur 1994).

During the C–T interval, the basin connected the circumglobal “Boreal” ocean with western Tethys. At this time, the central Western Interior region lay between 30° and 45°N paleolatitude (Fig. 1; Barron 1987; Scotese 1991). Numerical model simulations of climate for the time period suggest a warm equable Earth, weak meridional temperature gradients, and little or no polar ice (e.g., Barron and Washington 1982). General Circulation Model (GCM) experiments to analyze the effects of orbital forced changes in insolation suggest intensification of monsoonal circulation and fluctuations in the hydrologic cycle in the Northern Hemisphere (Barron et al. 1985; Glancy et al. 1986, 1993; Park and Oglesby 1991, 1994). Diverse paleoclimatic data support these predictions. For example, biogeography of marine invertebrates, botanical data, abundance of coals and deltaic deposits, character of paleosols, and stable-isotope evidence (Kauffman 1984; Pratt...
CENOMANIAN-TURONIAN MILANKOVITCH CYCLES

1984; Upchurch and Wolfe 1993; Ludvigson et al. 1994; Witzke and Ludvigson 1994) indicate warm temperate to subtropical climates with humid to subhumid conditions for the central Western Interior region. Abundance of storm deposits (e.g., Gustason 1989; Duke 1985) and paleobotanical evidence for seasonality in precipitation (Upchurch and Wolfe 1993) also support the monsoon hypothesis.

The Bridge Creek Limestone Member of the Greenhorn Formation records the maximum development of marine conditions and carbonate deposition in the Greenhorn cycle and is composed of rhythmic alternations between dominance of siliciclastic sediment and pelagic carbonate (Figs. 1, 2). These alternations, which form conspicuous limestone-shale bedding couplets, were among the units that Gilbert (1895) interpreted as the sedimentary expression of orbitally forced climate cyclicity. Although Gilbert (1895) was preceded by some 20 years in correlating geological phenomena to orbital influence on climate (e.g., Croll 1875; Blytt 1883), he was among the first to suggest the application of this relationship to chronostratigraphic reconstructions, and the first to advance multiple hypotheses for the linkage between climate and sedimentation in pre-Pleistocene strata. Over 70 years passed with relatively little attention paid to Gilbert’s ideas, until Hattin (1971) convincingly documented the widespread, synchronous deposition of the Bridge Creek limestone beds in the WIB. Although Hattin (1971) concluded that the bedding rhythms represented variations in terrigenous sediment supply superposed upon a relatively constant carbonate flux, he declined to speculate on a driving mechanism. Building on the later revelations of Hays et al. (1976) and Imbrie and Imbrie (1979) on orbital forcing of Pleistocene climate change, as well as the development and application of radiometric time scales to interpretation of Cretaceous sedimentary cycles (Kauffman 1977), it was Fischer (1980) who revived interest in Gilbert’s (1895) interpretations of the upper Cretaceous bedding rhythms. His work initiated a phase of growth in cyclostratigraphic research that continues to this day.

Fischer (1980) addressed two major issues in his reexamination of Gilbert’s (1895) work: (1) the timing of bedding cycles and their potential for application to chronostratigraphy; and (2) the mechanisms by which orbitally forced climate cycles are translated through a depositional system into bedding patterns. With regard to timing, Fischer noted that available radiometric data were not sufficiently refined to unequivocally establish periodicities in the Milankovitch band, but he used them as guidelines to determine reasonable rates of sedimentation and subsidence. He concluded that some upper Cretaceous bedding couplets have estimated durations and bedding features such as bundling (first noted by Schwarzacher 1954), which support interpretation of the precessional index. However, the calculated duration of the Bridge Creek bedding couplets did not match a known orbital period and the cycles did not appear to exhibit bundling. Later, Fischer et al. (1985) suggested that the Bridge Creek cycles represent the 41 ky obliquity cycle, but again cited poor age constraints as a source of considerable uncertainty. Most studies of the Bridge Creek Limestone tentatively conclude a Milankovitch forcing in the 20–40 ky range but note
that the record appears quite chaotic. Although Herbert and Fischer (1986) and later Park and Herbert (1987) demonstrated the power of Fourier techniques (spectral analysis) in establishing periodicity in rhythmically bedded successions, and some of these methods are particularly well suited to “noisy” time series, they have not yet been applied to the Bridge Creek Limestone.

As regards depositional mechanisms, Fischer (1980) expanded on Gilbert’s (1895) original hypotheses to arrive at three major climate-controlled drivers: (a) minor sea-level fluctuations, possibly glacio-eustatic in origin, that lead to oscillations in dominance between clay (restricted basin) and carbonate (open marine basin) deposition; (b) changes in wind direction and intensity, and thus currents, with resulting changes in sediment distribution and water-column stratification; and (c) changes in precipitation in western source areas with attendant effects on siliciclastic sediment supply, development of haloclines, and benthic oxygen deficiency. Based on this foundation, a host of investigators have used stratigraphic, sedimentologic, geochemical, and paleontologic evidence in efforts to discern the origin of the Bridge Creek bedding couplets (e.g., Kauffman 1977, 1988, 1995; Pratt 1984; Arthur et al. 1984; Arthur et al. 1985; Barron et al. 1985; Eicher and Diner 1985, 1989, 1991; Fischer et al. 1985; Arthur and Dean 1991; Pratt et al. 1993; Ricken 1993, 1994; and Savrda and Bottjer 1994), and still there is no consensus. Climate-controlled fluctuations in primary productivity have been suggested as an alternative to the more popular dilution/redox models (e.g., Eicher and Diner 1985), but the question remains largely unresolved.

## METHODS

Tests for periodicity in stratigraphic sequences thought to record Milankovitch cycles are based on measurements of selected physical parameters thought to reflect climatically controlled components of the depositional system. In Cretaceous hemipelagic and pelagic facies these commonly include measurements of variations in lithologic and geochemical characteristics of rhythmic bedding couplets. Counts of couplets, measures of couplet thicknesses, weight % calcium carbonate and organic-carbon, and quantitative estimates of rock color (grayscale densitometry, which serves as a proxy for variations in carbonate content; Herbert and Fischer 1986), have all been employed. Each type of analysis is best conducted on extremely fresh exposures where potential changes in bed thicknesses, chemical compositions, and/or rock colors due to surface weathering are minimized. The acquisition of a pristine core (USGS #1 Portland) through the Greenhorn Formation in the summer of 1992 was made possible by the Cretaceous Western Interior Continental Scientific Drilling Project (Dean and Arthur 1994), and provided an excellent opportunity to analyze the bedding couplets of the Bridge Creek Limestone. The core was drilled in a location where the Cretaceous strata were flat-lying and structurally undisturbed, resulting in total recovery. A 12.5 m interval of the core was examined and sampled for detailed lithologic and geochemical analysis in this study.

### Stratigraphy

High-resolution lithologic description and measurement of the USGS #1 Portland core was completed by Arthur and Sageman following collection and curation of the core by the USGS Core Research Center in Denver, Colorado. An example of the core material illustrating bedding cycles is shown in Figure 3, and a detailed measured section showing the study interval is shown in Figure 4. Correlation of beds to the Cretaceous reference section at Rock Canyon Anticline (approx. 40 km east) were made based on similarities in lithology, thickness and sequence of limestone beds, and positions of marker bentonites. These correlations, represented in Figure 4 by assignment of the Cobban and Scott (1972) bed numbers to the appropriate limestone beds, facilitated precise recognition of upper and lower contacts of the member and its subjacent and superjacent units (Figs. 2, 4). Standard Western Interior ammonite biozones key in the Cretaceous reference section for Colorado at Rock Canyon (Cobban 1984, 1985; Elder 1985; Kennedy and Cobban 1991), were extended to the #1 Portland core based on these lithologic correlations (Fig. 4).
lithologic characteristics of the bedding couplets, couplet thicknesses, and the number of couplets within a defined (dated) interval. To better quantify lithologic variations we performed analyses of weight % carbon content on samples 1 cm thick taken at 5 cm intervals through the well-developed limestone–marlstone bedding couplets of the core. The samples were crushed to < 0.002 mm and analyzed with a UIC coulometer. Values of weight % inorganic carbon (IC) were obtained by acidification with perchloric acid and weight % total carbon (TC) by combustion at 950°C in a stream of oxygen. CO₂ liberated by each process was titrated in a coulometer cell to determine IC and TC, respectively (Engelman et al. 1985). Weight % organic-carbon values (OC) were obtained by difference between IC and TC, and carbonate values (weight % CaCO₃) were calculated from IC based on stoichiometry of CaCO₃. The precision of coulometric analyses is commonly better than 1% of the carbon present. Because of slight irregularities in lithology and core recovery, some of the sampled intervals varied by 1 to 2 cm from the nominal 5 cm spacing. A cubic spline was applied to the slightly unevenly spaced “raw” geochemical data to obtain the necessary regularity for spectral analysis. Samples representing altered volcanic ash (bentonite) beds were considered to reflect instantaneous events and were edited out of the data series before spectral analysis.

As a complement to the geochemical data set, black-and-white photographs of the slabbed archive half of the #1 Portland core were scanned into 8-bit TIFF files and analyzed for variations in bed color using NIH image-processing software. The image-analysis program allows for a scan of optical density in which pixel values ranging from 0 (white) to 255 (black) are averaged over a user-selected area. In order to produce a pixel data set as closely comparable to the geochemical data as possible, 1-2 cm areas were scanned at 5 cm intervals corresponding to the locations of the geochemical samples. The scans average numerous adjacent rows of pixels to produce single values, which were spliced together from each photo segment to create a data series for spectral analysis (Fig. 4). Based on estimates of the sedimentation rate (see below), a 5 cm sample interval was adequate to test for cycles with periods corresponding to the main Milankovitch frequencies (> 16 ky). As with the geochemical data, values representing altered volcanic ash (bentonite) beds were not included, and a cubic spline was applied to insure regular spacing of data points.

Variations in trace-fossil content of pelagic and hemipelagic strata are thought to reflect changes in bottom and/or pore waters, and thus provide a history of benthic redox conditions (Savrda and Bottrij 1991). In collaboration with our description and geochemical sampling of the #1 Portland core, Savrda (1996) analyzed trace-fossil characteristics at 2 cm intervals through the Bridge Creek Limestone. The collected data include diversity of biogenic structures and maximum burrow diameter (MBD). A series of ichnocoenoses were identified by Savrda (1997), including: L. laminated strata; 1, small Planolites/Chondrites ichnocoenosis; 2, small Planolites/Taenidium ichnocoenosis; 3, small Planolites/Taenidium/Zoophycos ichnocoenosis; and 4, Thalassinoides/Teichichnus ichnocoenosis. Data on MBD, penetration depth, tiering, and trace-fossil diversity are combined to create an oxygen-related ichnocoenosis rank value (ORI, Fig. 4). The reference lines in the curve are interpreted to represent threshold oxygen values for the designated ichnocoenoses.

**RESULTS**

**Time Scales and Sedimentation Rate**

The Kauffman et al. (1993) and Gradstein et al. (1994) time scales were used to determine an age–depth relationship for the Bridge Creek Limestone in the #1 Portland core. The error ranges of the measured radiometric dates define minimum and maximum limits for study interval duration, and result in a range of sedimentation rates that best reflect the uncertainty in available temporal data (Table 1). The interval from the base of the Vascoceras diatrium Biorne (which is equivalent to the base of the Scolopenoceras gracile Biozone) to the top of the Mammites nodosoides Biozone
is appropriate for estimation of an average sedimentation rate (Fig. 4) because: (a) the lithostratigraphically defined top of the Bridge Creek Limestone does not coincide with a biozone boundary; (b) the bulk of the well-developed bedding couplets are within this interval; and (c) the bulk of the geochemical analyses were performed in this interval. Using the Kauffman et al. (1993) time scale for this interval, calculation of the average bulk sedimentation rate yields a value of 0.6 cm/ky. This value represents an effective sedimentation rate (Park and Herbert, 1987) which is not corrected for compaction or nondeposition.

The Gradstein et al. (1994) time scale differs from the Kauffman et al. (1993) scale in two respects: (a) average boundary dates vary slightly between the time scales, based on different methods of interpolation; and (b) the standard deviation of the C-T boundary date, which is used as the average error, is lower (± 0.2 My). Calculation of an average sedimentation rate based on the Gradstein et al. (1994) time scale yields a value similar to the Kauffman et al. (1993) time scale (0.5 cm/ky). Because the Kauffman et al. (1993) scale was developed directly from Western Interior biostratigraphic and geochronologic data, it probably represents the best temporal estimate for the Bridge Creek Limestone, and so we use the 0.6 cm/ky value. This value falls at the lower end of estimates of Bridge Creek sedimentation rate by previous authors (e.g., S = 0.7-2.1 cm/ky: Pratt, 1985; S = 0.5-1.0 cm/ky: Elder and Kirkland 1985), but our analysis
<table>
<thead>
<tr>
<th>Age at base</th>
<th>Interval Duration</th>
<th>Sedimentation rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y. diastemosis</td>
<td>0.6 (Ma)</td>
<td>1.7 (cm/ky)</td>
</tr>
<tr>
<td>M. anastomosis</td>
<td>18 (Ma)</td>
<td>0.59 (cm/ky)</td>
</tr>
<tr>
<td>Low K</td>
<td>3 (Ma)</td>
<td>0.35 (cm/ky)</td>
</tr>
<tr>
<td>High K</td>
<td>2.5 (Ma)</td>
<td>0.42 (cm/ky)</td>
</tr>
</tbody>
</table>

Notes: Interval thickness = 0.6 cm
Kaufman scale error: ±0.6 Ma
Grotzien scale error: ±0.2 Ma
Notes: Sedimentation rates not corrected for compaction.
The average errors of the respective radioactive data are used to establish minimum and maximum limits for ages of selected biostrome boundaries, and thus durations. Based on the calculated durations and the interval thickness, minimum, maximum, and average sedimentation rates are calculated for each time scale.

The rhythmic bedding of the Bridge Creek Limestone in the central Western Interior basin is its most conspicuous feature and has been described extensively. The definition of the bedding cycles is based on the alternation of lithologic characteristics between a relatively light-colored, carbonate-rich end member and a relatively dark-colored, clay-rich end member (described below as “hemicycles”). Visual identification of these hemicycles in outcrop is commonly facilitated by variations in bed color, bed thickness, ichnofabric, and induration/weathering profile (mainly a function of CaCO₃ content). Cores provide an excellent opportunity to better quantify the first three parameters, but lack the enhancement of bedding couplets that results from weathering processes. However, detailed analysis of weight % CaCO₃ simulate the weathering profile (Fig. 4), aid in the characterization of lithologies, and provide a more accurate indication of original deposition.

**Carbonate-Rich Hemicycle.**—Lithologies in this group include a series of “impure” carbonates such as limestones and marly limestones (CaCO₃ 75–93%; average values are 79% for marly limestones and 83% for micritic limestones). Some burrowed marlstones that form better indurated beds in the core (CaCO₃ from 65–75%) are also included in the group. In the core, bed colors of these facies range from very light gray to medium light gray or bluish gray, to medium gray, and typically correspond to pixel values of about 95–125; the darker colors are concentrated in burrows or associated with marlstones. Texture varies from micritic to chalky (or from mudstone to wackestone), and fabric is dominantly burrow mossed or bioturbated. Burrow density and diversity increase upward within beds, and the ichnofauna commonly includes Planolites, Chondrites, Taenidium, Zoophycos, Teichichnus, and Thalassinoides (Savrda 1997). Presumably as a result of oxic conditions and burrowing activity, % OC values are low in most carbonate-rich beds (<1%). Pyrite commonly is present in burrows, as well as finely disseminated throughout beds. Shell material scattered throughout carbonate-rich units includes foraminiferal tests, coccolith-bearing (fossil) pellets, and Inoceramus bivalve shells and shell fragments. Many of the Bridge Creek limestone beds have a thin (0.5–1.0 cm) top layer consisting of a concentric of this skeletal material, with foraminiferal tests being the most common constituent. Lenses and thin beds of skeletal limestone become very common within clay-rich hemicycles of the uppermost Bridge Creek Member. In general, the upper contacts of most micritic and marly limestone beds are sharp and the lower contacts are gradational over 2–5 cm. This reflects downward mixing of carbonate-rich muds by burrowers during deposition of the bed, and the abrupt termination of infaunal activity at the bed top. Carbonate-rich beds typically are 6–20 cm thick with an average value of about 14 cm. The basal micritic limestone bed of the Bridge Creek Member (bed #63: Fig. 4), however, has an anomalous thickness of 50 cm.

**Clay-Rich Hemicycle.**—Lithologies include marlstones (CaCO₃ 50–65%) and calcareous mudstones/calcareous shales (CaCO₃ 10–50%). In beds that are adjacent to ashes, bentonitic clay can be mixed in by burrowing to yield low CaCO₃ values (24–38%), but the average CaCO₃ content of most relatively clay-rich beds in the Bridge Creek Member is about 62%. Thus, the Bridge Creek is composed mainly of limestone–marlstone couplets. Fresh exposures of clay-rich facies range from medium light gray or olive gray to medium dark gray or dark olive gray, and in some cases, olive black. The corresponding pixel values are ~200–225. The beds are laminated to microburrowed or macroburrowed, but discrete burrows are not as well defined as in the carbonate-rich units. Organic-carbon content varies from <1% to 6.5% in the relatively clay-rich units. Percent OC values are uniformly low through the lower half of the member (with the exception of several beds in the upper N. juddii and lower W. devonense Biozones), but average about 3% OC in the upper Bridge Creek Limestone (Fig. 4). Clay-rich hemicycles tend to be thicker than the corresponding carbonate-rich beds, but thicknesses vary stratigraphically; average bed thickness is 41 cm in the lower part of the member but decreases to 29 cm in the upper part.

**Couplet Characteristics.**—Bridge Creek bedding couplets have been characterized based on descriptions of outcrop beds enhanced by weathering (e.g., Kaufman 1995; Ricken 1994), as well as through descriptions of bed color, fabric, and ichnofossils, and trends in geochemical parameters in cores (e.g., Arthur et al. 1985; Arthur and Dean 1991; Pratt et al. 1993; Savrda and Bottjer 1994). However, prior studies have either lacked the resolution necessary to determine all the variations in the record or have considered only a part of the Bridge Creek in detail (usually the lower part). Figure 4 shows the higher-resolution carbonate, organic-carbon, grayscale, and ORI curves from the #1 Portland core that make possible a multi-parameter definition of the bedding couplets.

Bedding couplets are defined from the base of the clay-rich hemicycle to the top of the immediately superjacent carbonate-rich hemicycle, a contact that is commonly sharp. For lithologically defined couplets (Fig. 4) the definition of hemicycles is based on core descriptions of bed color, bioturbation fabric, and bedding contacts. This method provides the lowest resolution in defining hemicycles. Comparison with the high-resolution carbonate record shows many substantial oscillations in weight % CaCO₃ that are not expressed as well-defined limestone beds in the section in Figure 4, and were thus overlooked as discrete hemicycles in the visual core description. Optical density measurements provide a more objective measure of bed color and have been successfully used as a proxy for carbonate content in other Cretaceous lime-marl successions (e.g., Herbert and Fisher 1986). However, rock color is not controlled solely by % CaCO₃ content. Variations in % OC and clay content, and mixing across bed boundaries due to burrowing, can alter color patterns. In the #1 Portland core, averaged pixel values show a moderate level of correlation with % CaCO₃ (r = −0.6). The correlation is not higher because: (1) some samples with relatively high carbonate content are dark in color (e.g., limestones into which darker sediment has been mixed by burrowers, as well as some high-carbonate marls that are quite organic-rich); and (2) some samples are dark in color but show low % OC values (including some mudstones that are micro- to macrobioturbated). These data suggest that the relationship between color and chemical composition is not always straightforward. Although the number of couplets defined on oscillations in pixel values is quite similar to that of % CaCO₃, the amplitude and position of individual oscillations do not match exactly. Nonetheless, most major color changes coincide with changes in chemical composition, at or
near limestone bed boundaries. Weight % CaCO₃ data provide the best primary record of oscillations in lithologic composition in the Bridge Creek Limestone (Fig. 4). Because certain samples include shell fragments or thin lenses of skeletal material, however, this method of couplet definition may produce scattered small peaks that could be spurious relative to the background depositional system. By comparing results among the lithologic descriptions, the % CaCO₃ record, and the pixel data, such anomalies can be filtered out.

Because the cores preserve a robust record of variations in burrowing activity within the Bridge Creek Limestone, ichnologic analysis offers a further tool to characterize the bedding couplets. Trends in MBD and ORI are quite similar through the #1 Portland core (Savrda 1997), and reflect changes in the intensity of bioturbation that are strongly correlated with trends in % CaCO₃ (Fig. 4). Although changes in benthic oxygen levels are the major factor thought to control bioturbation intensity, changes in substrate consistency due to the variation in sediment composition (% CaCO₃, % OC, clay content) may also have influenced the fauna.

Couplet Counts.—A common method to assess periodicity in rhythmically bedded sequences bracketed by radiometric dates is to count bedding couplets. By identifying every reasonable oscillation of the depositional system, this method seeks to assess the highest cycle frequency within the sequence. Establishment of cycle ratios is dependent on recognition of a systematic hierarchy of characteristics among the bedding couplets. However, the potential for bias in the process of couplet definition may pose a problem for this approach. For example, the definition of major vs. minor couplets is difficult to establish objectively because of changes in couplet characteristics throughout a stratigraphic sequence, and between different methods of recognition (e.g., core description vs. % CaCO₃ vs. pixel values vs. burrowing trends). Maximum couplet counts using these different methods produce a range of values from 23 to 45 couplets within the dated interval. Calculation of cycle periods based on the interval durations in Table 1 yield values ranging from 13 to 120 ky. Thus, this method mainly confirms that, within the constraints of available radiometry, the highest-frequency bed cyle of the Bridge Creek Member fall within the Milankovitch band (~ 20–100 ky).

Bundles.—The best qualitative indication of Milankovitch cyclicality in a bedding sequence is recognition of characteristic frequency ratios in lithologic variations such as bed thickness (e.g., the 1:5 precessional index ratio; Schwarzacher and Fischer 1982). Long-term variations in the carbonate record revealed by a 20-point moving average (shaded curve in Figure 4) include a 2.5–3.0 m oscillation that persists for about two cycles in the upper part of the study interval but becomes less clearly defined in the lower part. Given the estimated duration of the study interval (0.6–3.0 My), these oscillations would correspond best to the long cycle of eccentricity (~ 400 ky). Herbert and Fischer (1986) identified the 20 ky eccentricity signal in the APT-ALBAN PIORCOCO core, but it occurred in close association with cycles interpreted to represent the short eccentricity (100 ky) and precession (20 ky) signals, or the precessional index. Although a 1:5 ratio in bed characteristics has been described qualitatively in the lower part of the Bridge Creek Limestone (Savrda and Bottjer 1994), suggesting the precessional index, this pattern is not obvious in the upper part of the #1 Portland core.

Bed-Thickness Trends.—Variations in hemicycle and couplet thickness are also observed throughout the Bridge Creek Member. Figure 5 shows a scatterplot of weight % CaCO₃ vs. hemicycle thickness (hemicycles were defined based on CaCO₃ content). The shaded ellipse enclosing most of the data (trend A, Fig. 5) illustrates a series of hemicycles in which increasing bed thickness on average corresponds generally with decreasing CaCO₃. Arthur and Dean (1991) interpreted such a trend to reflect changes in silicilastic input superimposed on relatively constant fluxes of CaCO₃ and OC. Exceptions to the trend include a series of calcareous shale to marlstone units, mostly in the lower Bridge Creek Member (trend B, Fig. 5), as well as the basal limestone bed, which are all anomalously thick. The calcareous shale to marlstone units vary significantly in character. For example, the two thinnest hemicycles in trend B (units 68–72, Fig. 4, 5) have the lowest CaCO₃ values and are associated with thick bentonite beds, suggesting possible aperiodic diagenetic flows of volcanic ashfall. The two thickest hemicycles in this trend (units 85 and 87) lie at and just above the C-T boundary, are characterized by high % CaCO₃, and among the highest % OC values (of the lower study interval), and are not associated with bentonite seams or beds. These units may reflect anomalously high fluxes of organic matter to the sediment, compared to most hemicycles, as suggested also by Arthur and Dean (1991). A single hemicycle from the upper Bridge Creek is present in trend B (Beds 106–108). This unit has no well-developed bentonite seams, has high OC levels, and contains common thin skeletal limestone laminations. Processes associated with the formation of the skeletal limestone units may have influenced the thickness of this hemicycle, but a consistent relationship is not observed (other clay-rich hemicycles in the upper Bridge Creek Member include common skeletal laminates but are not anomalously thick).

The most anomalously thick carbonate-rich hemicycle in the study interval is the basal limestone (Bed 63). An explanation for this feature can be constructed on the basis of regional stratigraphic data. On the east flank of the Black Hills, South Dakota (Black Gap section; Frush and Eicher 1975), the stratigraphic interval that is equivalent to Bed 63 in central Colorado, defined by detailed biostratigraphy and lithostratigraphy, is represented by a series of five bedding couplets rather than a single thick limestone (Sageman 1991). The Black Gap site may have been more influenced by terrigenous sediment from the Sevier Orogenic Belt to the west, and thus was more sensitive to fluctuations in dilution during the onset of Bridge Creek deposition. In the central Colorado region, some combination of erosion and/or lack of elastic sediment delivery appears to have resulted in condensation of separate hemicycles into a single thick limestone bed.
This contrast reflects two main types of couplet, which are clearly defined in a carbon scatterplot in Figure 6. With the exception of about seven samples from the Cenomanian–Turonian boundary zone, most lower Bridge Creek samples plot along a vertical trend showing little change in OC for corresponding changes in CaCO₃. The trend of upper Bridge Creek samples has a significant slope by comparison, suggesting coupled changes in OC and CaCO₃. Note that the major change in couplet characteristics corresponds well with the end of the δ¹³C excursion interval at about 6 m above the base of our study interval (Fig. 4).

**Spectral Analysis**

Initial spectral analyses of the carbon and pixel data using a simple Fast Fourier Transform (FFT) technique (Sageman et al. 1993) suggested the possibility of cycle periods in the Milankovitch band. To improve the resolution of our spectral estimates we applied several other Fourier techniques to the high-resolution data sets from the #1 Portland core, including the Blackman–Tukey method (BTM), the maximum-entropy method (MEM), and the multitaper method (MTM) of Thomson (1982). BTM is a method for smoothing spectral estimates produced by the FFT. MEM uses a different model, which is well designed for noisy spectra that contain pure sinusoids or "harmonic components". The multitaper method uses an optimal set of orthogonal tapers (windows) to produce independent assessments of a spectrum. Frequencies that recur in spectral estimates from multiple tapers have a stronger likelihood of reflecting a monochromatic signal, and the method is especially useful for detecting weak harmonic components in noisy time series such as geological data (Park and Herbert 1987). Advantages of MTM over other methods include improved spectral resolution, more objective determination of tapers, and the availability of a statistical assessment (F-variance-ratio test) of the likelihood that the data contain a monochromatic signal at each discrete frequency (Yiou et al. 1994).

To apply the BTM and MEM we used a software package for X-Windows called Singular Spectrum Analysis (SSA) toolkit (see Dettinger et al. 1993). For the MTM, we used a program provided by J. Park and followed some of the procedures outlined by Park and Herbert (1987). First, in order to determine optimal MTM parameters for analysis of the core data (number of tapers, etc.), we generated and analyzed synthetic time series of modern orbital cycles using Berger’s (1978) astronomical calculations. These time series were constructed to match the characteristics of the Bridge Creek data sets in terms of the number of data points and the estimated time interval between points, calculated using the average sedimentation rate and interval thickness (Table 1). Although Berger’s (1978) orbital parameters are computed for the late Pleistocene to Recent, corrections have been calculated to reflect the dominant Milankovitch periods during Cretaceous time (Berger et al. 1989; Berger et al. 1992). We chose to develop the synthetic time series from the more complete modern data and to consider changes in the periods to Cretaceous values later, during analysis of the Bridge Creek spectra. We chose also to analyze the orbital components separately rather than Northern Hemisphere total insolation because of the poor fit of the latter to most pre-Pleistocene rhythmically bedded sequences tested with spectral techniques. By varying the parameters used in MTM analysis of the synthetic time series, which we took to represent an ideal record of Milankovitch forcing in Bridge Creek strata, we were able to determine the optimum approach for analysis of the geochemical and pixel data.

The most common difficulty in performing spectral analyses of geological data are the uncertainties in age–depth relations (Park and Herbert 1987; Kominz and Bond 1990). Even for sections with the best dating, detection of sinusoids with ratios similar to the modern (or corrected) orbital periods is the most reliable test for Milankovitch forcing in pre-Pleistocene geologic data (Park and Herbert 1987). In analyzing the Bridge Creek data sets we looked for the dominant "quasi-periods" (Berger 1984).
most commonly reported in studies of rhythmic bedding (e.g., Fischer et al. 1985), such as the 21 ky peak for precession, the 41 ky peak for obliquity, and the 100 and 400 ky peaks for eccentricity (E1 and E2). In addition, because the MTM has been successful in resolving additional periodic components of the complex orbital cycles (Park and Herbert 1987), we were alert to the possible presence of signals at 97 and 127 ky related to eccentricity (E1a and E1b), at 39 and 53 ky related to obliquity (O1 and O2), and at 19 and 3 ky related to precession (P1 and P2).

Our lithologic observations suggested that the best record of cyclicity would be found in the upper part of the study interval, and initial spectral estimates confirmed this: the results of spectral analyses of the whole interval showed some strength at frequencies suggesting Milankovitch forcing, but the results were inconsistent among the data sets and the significance levels were low. Similar tests of the lower interval alone were even more erratic, a result that supports our suspicion of aperiodic dilution and condensed and/or missing section in the lower Bridge Creek Member. Thus, we focused our analysis on the segment of data collected from meter 6.0 to meter 12.3 in the core (Fig. 4). We first analyzed the % CaCO3, % OC, and pixel data using BTM and MEM to determine the strength of any periodic signals in the spatial domain (cycles/meter) and to test for consistency among the data sets (Fig. 7). Next, we used MTM to improve the resolution of our spectral estimates (Fig. 8, Table 2).

Spectral Estimates.—The results of BTM and MEM analyses were quite similar, and only BTM results are reviewed here. The analysis of % CaCO3, % OC, and pixel data produced spectra with several strong peaks. Labeled A through E in Figure 7, these correspond respectively to about 0.4, 1.6, 3.0-3.2, and 4.0-4.2 cycles/meter. Weaker responses were observed at about 6.3 cycles/meter in the pixel data and 7-7.5 cycles/meter in all data sets (Fig. 7). Assuming an s value of 0.6 cm/ky, these peaks correspond approximately to E2, E1, O2, O1, and P (in order from A to E in Figure 7). The most notable differences among the BTM spectra are the large amplitude of the E2 peak in the CaCO3 data, the significance of the E1 peak in the pixel data, and the slightly stronger high-frequency responses of OC and pixel relative to CaCO3. The frequencies corresponding to O1 and O2 have significant amplitudes in all three spectra.

Results of MTM analyses are shown in Table 2. These include values for the frequency, amplitude, phase, period, and F-test value of frequencies with F-tests > 90% confidence for both the synthetic orbital data (used to calibrate MTM analysis parameters) and the three upper Bridge Creek Member data sets (representing observed values). Significant F-test values from MTM analysis of the synthetic time series indicate the predicted frequencies for eccentricity, obliquity, and precession (Table 2). These F-test results also suggest what to expect in terms of relative strength for the different frequencies associated with each of the orbital parameters. In each case, F-tests for isolated harmonics are much larger than F-tests for harmonic signals that occur in close proximity (Park and Herbert 1987). For the synthetic obliquity series, the 54 ky signal has a larger F-test than the 41 ky peak, possibly because of interference between the latter and the nearby signal at 39 ky. Similarly for precession, there is a dominant 18.9 ky peak and several smaller peaks at 22 to 23 ky (additional signals with > 95% confidence that appear in the synthetic time series include peaks at 29 and 35 ky). This phenomenon of neighboring peak interference may be exacerbated in geologic data because of bioturbational smearing or slight variations in sedimentation rate.

Figure 8 shows the amplitude spectra for % CaCO3, % OC, and pixel data with the corresponding plot of F-test peaks superimposed on it. F-test peaks with confidence levels above 90% that correspond to amplitude maxima are blackened. The % CaCO3 data show significant response at values corresponding to all three predicted Milankovitch frequencies (corrected to Cretaceous values; Berger et al. 1989, Berger et al. 1992). The most significant responses are for frequencies corresponding to P1, P2, O1, O2, and E1 at s = 0.6 cm/ky. The data show an O2 peak at 50 ky slightly stronger than the O1, a weak response for E1 at 102.6 ky, and two peaks in the precessional band at 22.4 and 20.0 ky (Table 2, Fig. 8). Spectral results for the % OC data show no significant F-tests for eccentricity, but good response for obliquity and precession (Table 2, Fig. 8). There is a strong F-test peak for O2 in the OC data at 51.9 ky and a lesser O1 peak at 40.0 ky, as well as several precessional peaks at 21.6, 19.9, and 19.4 ky. Unlike the two other data sets, the pixel record suggested a precessional index signal (precession modulated by eccentricity). Note the peaks at 399.2, 99.4, 23.1, and 19.3 ky in the pixel data with F-tests greater than the 95, 99, 95, and 99% confidence levels, respectively (Table 2, Fig. 8). A 52.4 ky peak suggests O2, but there is only a weak response at the 40 ky frequency (F-test < 90% confidence).

Several conspicuous F-test peaks appear in Figure 8 that do not match predicted Milankovitch signals and deserve mention. The first group includes the peak at about 63 ky in each of the analyzed data series (> 95% confidence level) and the 32 ky peak in % OC data (also > 95% confidence level; Fig. 8). Because F-test values are solely indications of the reliability of the spectral estimate for a given frequency, strength in both the amplitude spectrum and the F-test are required to interpret a periodic signal in
TABLE 2.—Results from MTM analysis of (1) model orbital parameters based on Berger (1978) and (2) the three data series of the upper Bridge Creek Limestone (only frequencies with F-tests above the 90% confidence level are shown).

<table>
<thead>
<tr>
<th>Model Orbital Parameters</th>
<th>Bridge Creek Limestone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (cycles/ky)</td>
<td>Amplitude (°/1000 ky)</td>
</tr>
<tr>
<td>CaCO3, 5.3°, 0.6 cmky, upper BC</td>
<td>0.262/1000</td>
</tr>
<tr>
<td>E2</td>
<td>0.0428</td>
</tr>
<tr>
<td>E1a</td>
<td>1.0137</td>
</tr>
<tr>
<td>E1b</td>
<td>1.7822</td>
</tr>
<tr>
<td>2.712</td>
<td>2.826/1000</td>
</tr>
<tr>
<td>3.1250</td>
<td>2.699/1000</td>
</tr>
<tr>
<td>3.3691</td>
<td>1.482/1000</td>
</tr>
<tr>
<td>3.8037</td>
<td>1.686/1000</td>
</tr>
<tr>
<td>4.7485</td>
<td>5.865/1000</td>
</tr>
<tr>
<td>Oligocene, 3.3-Pl, 123 yrs. @ 0.6 cmky</td>
<td>0.1270</td>
</tr>
<tr>
<td>0.9570</td>
<td>0.00002</td>
</tr>
<tr>
<td>1.7866</td>
<td>0.00009</td>
</tr>
<tr>
<td>O2</td>
<td>3.1055</td>
</tr>
<tr>
<td>O1</td>
<td>4.0615</td>
</tr>
<tr>
<td>5.7115</td>
<td>0.00400</td>
</tr>
<tr>
<td>8.1201</td>
<td>0.00004</td>
</tr>
<tr>
<td>Precession, 3.3-Pl, 123 yrs. @ 0.6 cmky</td>
<td>0.5375</td>
</tr>
<tr>
<td>2.9907</td>
<td>1.560/1000</td>
</tr>
<tr>
<td>4.2773</td>
<td>1.346/1000</td>
</tr>
<tr>
<td>4.7413</td>
<td>1.296/1000</td>
</tr>
<tr>
<td>5.2459</td>
<td>2.106/1000</td>
</tr>
<tr>
<td>P2a</td>
<td>7.0088</td>
</tr>
<tr>
<td>P2b</td>
<td>7.4609</td>
</tr>
<tr>
<td>P1</td>
<td>8.7789</td>
</tr>
</tbody>
</table>

Each analysis used five 3.3-Pl tapers, 123 data points, and minimum padding. All periods were calculated using a sedimentation rate of 0.6 cmky. The dominant Milankovitch frequencies are designated as E1, E2, etc. in the left, and their F-tests and period values are printed in bold. Frequencies in the upper Bridge Creek Limestone data with F-test values above the 90% confidence level that correspond to the dominant orbital periods are also indicated by bold print.

The data. But the 63 and 32 ky frequencies correspond to well-defined lows in the amplitude spectrum, and their high F-test results are significant. The second group of unpredicted F-test results includes peaks at 50 to 52 ky in each data set and at 26 ky in the pixel data. Unlike the 63 and 32 ky signals, these frequencies coincide with strength in the amplitude spectra. Although the third term in Berger’s (1978) orbital time series for obliquity is 53.6 ky, and the adjustment for Cretaceous time would reduce that value slightly (making a closer match to the result in Figure 8), the response at this frequency should be significantly weaker than the 40 ky signal, not stronger as observed in our results. Possible explanations for these results include overtones or interference tones between different frequencies, similar to those documented by Park et al. (1993) in Upper Cretaceous deep-sea carbonates. The signal at about 50 ky could reflect merely the beat of eccentricity, or the beat frequency may have amplified the normally weaker O2 signal. This explanation applies well to % CaCO3 and pixel data but does not account for the 52 ky signal in the OC record where the response at E1 is lacking. Other possible causes include distortion of the time scale within the time series due to minor fluctuations in sedimentation rate (although it is unclear why this would selectively affect O2), red-noise enhancement, or nonlinear amplification within the climate/depositional system. The 26 ky signal is the interference beat between P1 and O1. Why it is expressed only in the pixel data is not clear.

According to Thomson (1990), the MTM may produce a number of random F-tests at the 90% confidence level equal to approximately 10% of the number of data points being analyzed. The odds that such random peaks would match the predicted ratio of the orbital periods is, however, exceedingly small. To assess the validity of our F-tests results, and to evaluate the variability among the different data sets used, we calculated an average frequency value for all possible orbital signals with at least two F-tests > 90% confidence among the CaCO3, OC, and/or pixel data. Standard deviations for these averaged frequencies were converted to period values and reflect the low level of temporal error among the different data sets (Table 3). Furthermore, the ratio between the period values averaged from the CaCO3, OC, and pixel data is extremely close to that predicted by theory for short and long eccentricity (E1 and E2), for the two largest obliquity signals (O1 and O2), and for two major components of precession (P1 and P2) corrected to their Cretaceous values (Table 3).

Summary of Results

Qualitative analyses of the lithologic and geochemical characteristics of Bridge Creek bedding couplets provide support for the interpretation of a relationship between orbital forcing and the depositional system. Estimates of periodicity for the maximum number of defined bedding couplets in the member are imprecise but fall within the Milankovitch band. Similarly, trends defined by a 20-point moving average of CaCO3 data could reflect the long eccentricity cycle (E2) but do not necessitate a periodic signal. A major conclusion of these analyses is that the limestone–marlstone bedding patterns of the Bridge Creek Member are quite complex. The member as a whole includes secular variations in lithologic and geochemical characteristics, as well as in burrowing trends. Such variations are most likely influenced by aperiodic changes in the fluxes of different components to the substrate, in productivity levels, and/or in redox conditions, which were significant in the lower part of the study interval (i.e., during...
Fig. 8.—Plots of MTM results for A) % CaCO₃, B) % OC, and C) pixel data from the upper Bridge Creek Limestone. Included curves represent the amplitude spectra (upper black lines) and superimposed F-test peaks (lower stippled lines). For the y axes, the spectral amplitude scales are on the left, the F-test scales on the right. The 90, 95, and 99% confidence limits for F-tests are indicated by dashed lines in each plot. The blackened F-test peaks represent frequencies with values > 90% confidence corresponding to orbital parameters; bold numbers show the cycle periods assuming $\lambda = 0.6$ cm/ky.

Table 3.—For MTM spectral peaks with at least two F-tests > 90% confidence level among the three data series, calculation of the average frequencies (f) and their standard deviations, the corresponding periods using a sedimentation rate of 0.6 cm/ky, and the ratio between the different frequencies.

<table>
<thead>
<tr>
<th></th>
<th>E2</th>
<th>E1</th>
<th>O2</th>
<th>O1</th>
<th>P2</th>
<th>P1</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCO₃</td>
<td>&gt; 95</td>
<td>&gt; 90</td>
<td>&gt; 95</td>
<td>&gt; 95</td>
<td>&gt; 95</td>
<td>&gt; 90</td>
</tr>
<tr>
<td>OC</td>
<td>&lt; 90</td>
<td>&gt; 95</td>
<td>&gt; 95</td>
<td>&gt; 95</td>
<td>&gt; 90</td>
<td>&gt; 90</td>
</tr>
<tr>
<td>Pixel</td>
<td>&gt; 95</td>
<td>&gt; 99</td>
<td>&gt; 95</td>
<td>&lt; 90</td>
<td>&gt; 90</td>
<td>&gt; 99</td>
</tr>
<tr>
<td>f (cycles/m)</td>
<td>0.432</td>
<td>1.65</td>
<td>3.23</td>
<td>4.16</td>
<td>7.44</td>
<td>8.51</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>0.02</td>
<td>0.09</td>
<td>0.07</td>
<td>0.02</td>
<td>0.26</td>
<td>0.17</td>
</tr>
<tr>
<td>Period (ky)</td>
<td>385 8</td>
<td>101</td>
<td>516</td>
<td>40.06</td>
<td>224</td>
<td>19.58</td>
</tr>
<tr>
<td>Observed ratio</td>
<td>3.79</td>
<td>0.99</td>
<td>0.51</td>
<td>0.39</td>
<td>0.22</td>
<td>0.19</td>
</tr>
<tr>
<td>Predicted ratio</td>
<td>4.13</td>
<td>1.02</td>
<td>0.53</td>
<td>0.41</td>
<td>0.23</td>
<td>0.19</td>
</tr>
</tbody>
</table>

The ratio is calculated by setting the peak with the strongest response (E2) to 0.507 (equivalent to its estimated Cretaceous value) and scaling the other values accordingly. The predicted ratio between E2, E1, O2, O1, P2, and P1 is also shown. Based on the standard deviations, the error in period estimates among the different data series is E2 $\pm 18$ ky, E1 $\pm 28$ ky, O2 $\pm 1.9$ ky, O1 $\pm 0.2$ ky, P2 $\pm 6.15$ ky, and P1 $\pm 0.38$ ky.

OAE II; Fig. 4). Although spectral techniques can provide a means to quantify periodicities in a cyclic geologic time series, the periodic nature of the data cannot be determined if stochastic processes overwhelm or distort the periodic ones. The upper part of the study interval contained a more consistent record of sedimentary cyclicity, and was selectively analyzed for periodic signals relative to precession, obliquity, and eccentricity.

The results of the spectral analyses provide quantitative support for orbital forcing of sedimentation in the Western Interior during early Turonian time. In addition, application of the method helped to constrain interpretations of how orbital forcing was (or was not) translated into the sedimentary record. The investigated data series show evidence for periodic signals corresponding to frequencies that appear to represent six of the dominant orbital parameters (P1, P2, O1, O2, E1, E2), as well as some possible interference effects. Among the different data series there is an average temporal error of 2.4% for the different period estimates (Table 3). The range in these results may reflect differences in both the manner and degree to which alternative methods of lithologic measurement record stratigraphic variations, as well as differences in the response of related components of the depositional system to forcing factors. Among the three data sets, CaCO₃ showed the most complete response for frequencies approximating the six orbital signals, pixel data showed the most commonly seen pattern of precession and eccentricity cycles, and OC showed an uncharacteristic combination of strong obliquity and precession (Fig. 8). With an average sedimentation rate of 0.6 cm/ky and our 5 cm sampling interval, the P1 signal of precession (19 ky) lies close to the Nyquist frequency of the data (16.7 ky). Although this could lead to aliasing bias in the event of slight variations in sedimentation rate, a P1 signal was clearly expressed in our data, especially the pixel data set. The robustness of this result was confirmed by analysis of a larger pixel data set that contains 16,000 data points (representing a sample interval of approximately 1 mm).

Despite the presence of P and E signals in the upper Bridge Creek spectra, visual inspection of the bedding pattern does not suggest the familiar 1:5 ratio of other Cretaceous rhythmically bedded sequences (Fig. 4). To improve our understanding of the relationship between the bedding patterns of the Bridge Creek Member and the presumed orbital cycles detected through spectral analysis, we performed an additional experiment (Fig. 9). Assuming that variations in phase and amplitude of the combined E, P, and O cycles might produce a complex pattern of bedding, we modeled the orbital data as a linear combination of seven pure sinusoids representing the dominant orbital frequencies. These are P1, P2, O1, O2, E1a, E1b, and E2, which we corrected to their Cretaceous frequency values based on Berger et al. (1989), Berger et al. (1992), and Park and Herbert (1987). In this experiment, we used a linear least-squares fit to determine the amplitude and phase values that would optimize the fit of the integrated synthetic time series to the Bridge Creek % CaCO₃ record (Fig. 9). Consideration of the relative amplitude values produced in the least-squares calculation
suggests which periods may be dominant in the % CaCO₃ record if it is a mixture of multiple signals (Table 4). It must be emphasized that this approach seeks to model the mixing of independent sedimentary signals that were influenced by distinct climatic cycles, which in turn were forced by orbital parameters, rather than to emulate the direct mixing of the orbital signals themselves to produce, for example, total insolation at a particular latitude. Thus, the phase and amplitude of the orbital parameters observed in the Pleistocene may be significantly modified. The strongest signal in the synthetic was E2, followed by O2, E1a and b, P1, and P2. These results suggest that long eccentricity and perhaps interference effect between obliquity and eccentricity/precession are the most important factors influencing the bedding couplets of the upper Bridge Creek Limestone. This corroborates the recognition of a long eccentricity cycle in the lithologic analyses and is consistent with the marked obliquity signal at about 4 cycles/meter in all of the MTM amplitude spectra (Figs. 7, 8).

**DISCUSSION**

For over a century previous workers have concurred that the bedding couplets of the Bridge Creek Limestone represent manifestations of periodic changes in the depositional system produced by orbital forcing of climate (e.g., Gilbert 1895; Kauffman 1977; Fischer 1980; Arthur et al. 1984; Barron et al. 1985; Elder 1985; Fischer et al. 1985; Pratt 1985; Arthur and Dean 1991; Pratt et al. 1993; Savrda and Bottrill 1994; Kauffman 1995). Thus, although our study represents the first application of quantitative (spectral) methods to test the Milankovitch hypothesis in these rocks, some evidence of orbital periodicity was not unexpected. The greater significance of this study pertains to the questions of which orbital cycles are represented and what depositional mechanisms are responsible for their preservation (or lack of preservation), issues on which Bridge Creek cyclostratigraphers have not always agreed:

1. **Which** orbital cycles are represented in the member? Estimates have ranged from 20 to 40 to 80 to 100 ky. Although the 1:5 pattern of the precessional index is well documented in Albian-Cenomanian strata of the European Tethyan realm (Herbert and Fischer 1986) and is present in the more carbonate-rich F. Hays Limestone (Fischer et al. 1985; LaFerriere et al. 1987), a unit deposited only 5 My later in the Western Interior (Obradovich 1993), this pattern is not consistently expressed in the Bridge Creek Limestone. Further, the even bedded pattern characteristic of units thought to be dominated by obliquity (Fischer et al. 1985) is also lacking in the Bridge Creek Member.

2. **What** depositional mechanism is responsible for the alternation between carbonate-rich and clay-rich sedimentation? Although many recent studies have presented evidence in support of a coordinated dilution/redox model in which changes in the hydrologic cycle control delivery of silici-clastic sediment and stratification of the water column (e.g., Arthur et al. 1984; Arthur and Dean 1991; Pratt et al. 1993), other workers have argued for the role of climate-controlled fluctuations in carbonate productivity (e.g., Eicher and Diner 1985, 1989, 1991; Arthur and Dean 1991).

By confirming the presence of periodic variations in lithology and geochemistry that approximate the ratio of known orbital periods, by delineating the relative magnitudes of these cycles, and by documenting varia-

---

**Table 4**—Periods, their amplitude and phase values, and a ranking indicating their relative importance in the least squares fit to the %CaCO₃ data from the Bridge Creek Limestone for the seven sinusoids used to create the synthetic curve in Figure 9.

<table>
<thead>
<tr>
<th></th>
<th>E1a</th>
<th>E1b</th>
<th>E1</th>
<th>E2</th>
<th>O2</th>
<th>O1</th>
<th>P2</th>
<th>P1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Period</td>
<td>413</td>
<td>127</td>
<td>97</td>
<td>507</td>
<td>188</td>
<td>22.9</td>
<td>21.7</td>
<td></td>
</tr>
<tr>
<td>Amplitude</td>
<td>6.85</td>
<td>2.62</td>
<td>3.33</td>
<td>4.44</td>
<td>0.09</td>
<td>0.31</td>
<td>1.44</td>
<td></td>
</tr>
<tr>
<td>Phase</td>
<td>109</td>
<td>-77</td>
<td>-90</td>
<td>85.1</td>
<td>-56</td>
<td>88.2</td>
<td>-0.9</td>
<td></td>
</tr>
<tr>
<td>Rank</td>
<td>1</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

**Fig. 9**—A synthetic curve of the orbital parameters was constructed from seven sinusoids including three eccentricity (413, 127.6, and 97 ky), two obliquity (50.7, 38.8 ky), and two precession (22.9, 21.7 ky) terms. These values represent the dominant terms adjusted to Cretaceous time following Berger et al. (1992). By using a linear least-squares method and varying the amplitude and phase of these signals, the fit of the synthetic curve (dashed line) was optimized to the Bridge Creek % CaCO₃ curve (solid line). Tick marks on the right indicate E2 (400 ky) and E1 (100 ky) intervals.
tions in their expression through the study interval, our analysis reveals much about the dynamics of Bridge Creek Limestone deposition. The complex pattern of the bedding couplets appears to reflect the competing influences of different orbital signals that were expressed through separate pathways of the different sedimentary components. These pathways include fluvial input and distribution of fine-grained siliciclastic sediment (clay) in the basin, production and preservation of marine organic matter, and production of calcium carbonate (Arthur and Dean 1991; Ricken 1993, 1994).

It has been argued that the master control on these pathways was the hydrologic cycle, which, in turn, was sensitive to Milankovitch-scale climate changes (e.g., Barron et al. 1985). The balance between evaporation and precipitation is thought to have influenced: (a) weathering and erosion, fluvial transport, and the supply of fine-grained sediment to the basin; (b) fresh-water input and development of salinity stratification, with consequent implications for oxygenation of bottom waters and OC preservation; and (c) sea surface temperature, salinity, and circulation patterns, with implications for the ecology of planktic communities and production of CaCO₃. The Western Interior seaway was also subject to a unique set of conditions: the basin developed into a meridional seaway as rising sea level reached a critical threshold, resulting in the mixing of influences from the low-latitude evaporative belt and Tethyan ocean, and the high-latitude precipitation belt and Boreal sea (e.g., Hay et al. 1993). Thus, relative sea-level change also exerted an important control on depositional processes through its effect on basin size, depth, and configuration, as well as through control of sediment storage and delivery during high-frequency transgressive and regressive events.

Variations in couplet development provide clues to the behavior of the different depositional pathways in the WIB. During deposition of the Greenhorn Formation, rising sea level led to the establishment of normal marine conditions and an increase in CaCO₃ production in surface waters (Tethyan influence). This occurred concomitantly with a reduction in siliciclastic supply to the basin due to continued transgression, flooding of marginal marine and estuarine regions, and rapid subsidence of the western foredeep. The combination was sufficient to initiate limestone formation at the base of the Bridge Creek Limestone, and it was maintained rhythmically throughout the member. However, bedding cycles that preserve the influence of orbital forcing sufficiently to allow confident spectral estimates are present only in the upper half of the Bridge Creek Member.

Our analyses suggest that preservation of the orbital signal was perturbed in the lower part of the study interval by aperiodic changes in clay input related to volcanic ashfall events, by condensation and erosion possibly due to high-frequency relative sea-level changes, and by anomalous water-column conditions related to the oceanic anoxic event (OAE II), the isotopic record of which begins just prior to the onset of Bridge Creek deposition and continues until the earliest Turonian (Fig. 4). The pattern of OC preservation through the δ¹³C excursion is not only atypical of other examples of OAE II (Schlanger et al. 1987), it is also unlike that of upper Bridge Creek bedding couplets: the lower part of the excursion interval is characterized by a decrease in preserved OC and an increase in burrowing activity (Arthur and Sageman 1994), suggesting diminished rather than intensified anoxicity (Fig. 4). Bedding couplets mainly show a shift in CaCO₃ from one hemicycle to the other, with little change in OC content (Fig. 6). This pattern changes near the C-T boundary, where the combination of high OC levels and increased hemicycle thickness suggests a pulse in organic-matter production. This may reflect input of nutrient-rich waters from the expanded oceanic oxygen minimum zone, which would have had a higher likelihood of influencing the basin from the south as sea level rose (Slingerland et al. 1996). Collectively, these interpretations suggest that the production (and preservation) of organic matter was not continuously coupled with the production (or concentration) of carbonate.

The preservation of Milankovitch ratios in the bedding couplets of the upper Bridge Creek Member suggests that the different components of the depositional system (clay input, OC preservation, CaCO₃ production) became better coupled following OAE II. Increased sensitivity of the depositional system logically corresponds to peak sea level, the greatest extent of pelagic conditions, and the most uninterrupted record of sedimentation. The couplets show opposite trends in CaCO₃ and OC content from one hemicycle to the other (Fig. 6), reflecting a more regular oscillation between the two end-member depositional phases. This indicates that changes in OC production and/or bottom-water oxygenation were in phase (but opposite to) changes in CaCO₃ production and/or siliciclastic dilution. So far, application of a definitive method to assess changes in OC or CaCO₃ production through a bedding couplet has not been demonstrated. Precipitation/runoff cycles offer a compelling simple mechanism to explain carbonate dilution and redox conditions favorable for OC preservation, and much evidence has been presented in defense of the dilution/redox model (Arthur et al. 1984; Arthur et al. 1985; Pratt 1984; Arthur and Dean 1991; Pratt et al. 1993). Problems with this model include lack of microfossil evidence for freshened surface waters during clay-rich hemicycles (Eicher and Diner 1985, 1989, 1991), as well as low OC enrichment in most shale hemicycles of the lower Bridge Creek Member (suggesting that CaCO₃ dilution was not always accompanied by water-column stratification at this time).

Evidence in support of a modification of the dilution/redox hypothesis comes from spectral analyses of the upper Bridge Creek bedding couplets. These analyses indicate that each of the dominant orbital cycles is present in the section. However, there is a range of expression for different cycles among the different data records. The % CaCO₃ record shows better response for the P (and thus E) signal, whereas the % OC record shows better response for the O signal. These data suggest that carbonate production and/or dilution, and OC production and/or preservation, had different levels of sensitivity to different orbital cycles. In support of this possibility we offer three observations: (1) different orbital parameters may simultaneously affect different parts of the climate system at different latitudes; (2) different parts of the climate system may preferentially affect different components of the depositional system (such as CaCO₃ production, organic-matter production in noncalcareous plankton, clay input, and OC preservation); and (3) a meridional seaway has the necessary configuration to be influenced by multiple signals generated at different latitudes.

The modified hypothesis states that both carbonate production and siliciclastic dilution play a role in the development of the Bridge Creek bedding couplets. But carbonate (nannofossil) production was mainly influenced by precessional cycles (modulated by eccentricity), and the precessional effect was stronger at lower latitudes (Tethys region). In contrast, the obliquity cycle had a stronger influence on precipitation/runoff processes in more northern latitudes, and this produced the dominant overprint through siliciclastic dilution. The precessional signal still influenced CaCO₃ production, but its expression in the seaway was weaker. OC preservation was strongly coupled with dilution in the upper Bridge Creek Member, and OC spectra reflect the dominance of the obliquity cycle. But variations in the entire OC record suggest that productivity of organic plankton may have been independent of changes in CaCO₃ or clay input. Whether increased OC preservation in the clay-rich hemicycles resulted from enhanced stratification or from a change in the planktic population due to increased input of freshwater (and land-derived nutrients) is unknown. However, the dominance of OC-poor shale hemicycles during OAE II illustrates that OC preservation was not strictly coupled with dilution but depended on a third factor (such as the productivity of noncalcareous plankton) that was subject to the oceanographic influence of the OAE.

If our hypothesis is correct, the complex bedding pattern in the Bridge Creek Limestone is explained as a product of constructive and destructive interference between different depositional pathways with variable sensitivity to different orbital cycles. Modeling studies provide qualitative support for the modified dilution/redox/productivity hypothesis. For example, Park and Oglesby (1991, 1994) performed a series of GCM simulations for Cretaceous time that suggest that the climate system was sensitive to
both precession and obliquity at 70 and 100 Ma. While many authors have commented on the strength of the precessional signal at lower latitudes (e.g., Oglesby and Park 1989), Park and Oglesby's (1991) experiments suggested sensitivity of the hydrologic cycle over North America to the obliquity cycle. It stands to reason that variations in Northern Hemisphere precipitation would be most strongly expressed in the high-latitude precipitation belt, or over the more northern part of the Western Interior seaway.

In another modeling study aimed at understanding the circulation of the Western Interior sea, Slingerland et al. (1996) concluded that the basin acted like a large estuary, exporting surface waters on the eastern side of the northern aperture and the western side of the southern aperture. Losses were balanced by inflows of Tethyan and Boreal water that were distributed
in the seaway by large counterclockwise gyres. Thus, waters sourced in the lower latitudes would tend to flow north along the eastern half of the basin, and waters sourced at higher latitudes would flow south along the western half. Both water masses would exert an influence on the central part of the seaway, their relative importance depending on sea-level changes and resulting changes in basin geometry.

Figure 10 shows a graphic summary of the data for lithology, pixel values, weight % CaCO₃, and bioturbation for the Bridge Creek Limestone, and compares the bedding pattern in the upper part of the study interval to a plot of the major orbital cycles for the last 800 ky (from Berger 1984). In this plot, the obliquity cycle is blackened to reflect dominance. Although there are clearly differences between the orbital curves and the Bridge Creek data, this is to be expected, given differences in period and phase between Cretaceous and Pleistocene time. What is striking, however, is the correspondence between the long eccentricity pattern and the % CaCO₃ record, and between obliquity peaks and peaks in % CaCO₃ and bioturbation. The lack of closer correlation is interpreted to be a result of the variable influence of the higher-frequency precessional cycles, which would constructively and destructively interfere with the development of the bedding coupllets.

CONCLUSIONS

The bedding coupllets of the Bridge Creek Limestone Member have long been thought to represent Milankovitch cycles. However, low-resolution geochronologic data, intervals of condensed or missing section, and complexities in the bedding patterns have made delineation of the cycles difficult. Because of this, efforts to interpret the mechanisms of cyclic sedimentation have been impeded. In this study, new data and new methods were applied to the problem: (a) new high-resolution Ar-Ar radiometric dates, resulting in an improved estimate of the age–depth relationship for the study interval; (b) high-resolution documentation of lithologic variations resulting from analysis of the USGS #1 Portland core. Collected data included detailed visual descriptions, quantitative analyses of weight % CaCO₃, weight % OC, and optical densitometry of core photographs; (c) spectral analysis of the three complementary analytical records using several spectral methods (especially MTM). The results indicate that:

(1) The bedding coupllets of the Bridge Creek Limestone Member preserve a complex record of orbital cyclicity. Spectral analyses indicate cycles corresponding to precession, obliquity, and eccentricity, as well as evidence of interference between different cycles.

(2) The complex bedding pattern of the interval appears to result from the competing influences of different orbital cycles that were variably expressed through different pathways of the depositional system. Our analysis suggests that the effect of obliquity on Northern Hemisphere climate produced changes in freshwater input resulting in dominance of a coupled dilution/redo cycle. The effect of precession (and eccentricity) on low-latitude climate influenced Tethyan surface waters and their planktic (nannofossil) communities, which were imported northward into the Western Interior Seaway. Fluctuations in carbonate production reflect this influence. Production and preservation of organic matter was coupled with these other processes at times, but not always, indicating an independent depositional pathway.

(3) Variations in cycle expression through the Bridge Creek Member provide a high-resolution record of changes in the depositional system, revealing intervals of unusual condensation and aperiodic dilution. The recognition of these intervals aids greatly in the interpretation of Cenomanian–Turonian depositional history. Despite these variations, the approximate duration of the Bridge Creek based on cycle interpretation is in close agreement with estimates from the most recent geochronologic analyses.

(4) A possible explanation for the increased dominance of obliquity in the upper Bridge Creek bedding cycles (and consequent interference with the precessional signal) is that global burial of organic matter during OAE II led to decrease in atmospheric CO₂ levels and climatic cooling (Arthur et al. 1988), which in turn enhanced the effect of the northern obliquity dominated climate zone on the basin’s depositional system.

(5) Future work must be aimed at improvements in dating and/or better determination of sedimentation rates, filtering of the data series to improve spectral estimates, testing for meridional trends in the record of bedding coupllets, and better discrimination of the differences between clay-rich and carbonate-rich hemicycles (e.g., assessment of changes in primary producer communities and/or detrital sources).

ACKNOWLEDGMENTS

The authors thank C. Savrda for use of ichnologic data in this study, and C. Savrda and T. Bralower for collaboration in the investigation of Bridge Creek limestone–marlstone cyclicity. We also thank J. Park and M. Komniz for helpful reviews of this manuscript. This study was an outgrowth of the Western Interior Seaway Drilling Project, funded in part by the Department of Energy and The United States Geological Survey.

REFERENCES


Bluyt, A., 1883, Om vekselvæsken og dens mulige betydning for ildsætningen i geologien og lærer om arternes forandring: Veterinærl-selskabs Forhandlinger, Christina, no. 9, p. 31.


THOMSON, D.J., 1982, Spectrum estimation and harmonic analysis: Institute of Electrical and Electronics Engineers (IEEE), Proceedings, v. 70, p. 1025–1096.


Received 15 March 1996; accepted 22 August 1996.