Resolving Milankovitchian controversies: The Triassic Latemar Limestone and the Eocene Green River Formation

Stephen R. Meyers Department of Geological Sciences, University of North Carolina at Chapel Hill, Chapel Hill, North Carolina 27599-3315, USA

ABSTRACT

Although orbital forcing is commonly proposed as the driver of ancient sedimentary rhythms, the lack of adequate independent time control (radio isotopic data) to calibrate these cycles has stood as a major challenge to evaluation of the hypothesis. Here I apply a new statistical approach to evaluate cyclicity in two historically important rhythmic units for which orbital forcing has been proposed: the Triassic Latemar Limestone (Dolomites, Italy) and the Eocene Green River Formation (Wyoming, USA). A major advance of the new method is its explicit evaluation of the null hypothesis of no orbital signal. The null hypothesis can be rejected with a high degree of confidence in the Latemar Limestone (probability <0.30%) and Green River Formation (probability <0.07%). The analyses also resolve controversies about the specific orbital calibrations at each site. Both data series reveal the expected precession, obliquity, and eccentricity orbital components, and yield astrochronologies that are consistent with proposed radio isotopic based time scales.

Keywords: astrochronology, cyclostratigraphy, orbital time scale, Milankovitch.

INTRODUCTION

Among the numerous geochronologic methods available, astrochronology has emerged as one of the most important tools for refinement of the geologic time scale. Portions of the Gradstein et al. (2004) geologic time scale rely upon orbital-tuning methods, and such techniques are certain to increase in prominence due to the promise of unprecedented high-resolution geochronologies in pre-Pleistocene strata (Hinnov, 2005; Hinnov and Ogg, 2007). Despite its pivotal role in geologic time scale development, a fundamental shortcoming of essentially all pre-Pleistocene cyclostratigraphic studies has been the lack of sufficient independent time control (e.g., radiometric data) to calibrate observed spatial rhythms to temporal periods, and thus directly confirm the orbital tempo. This shortcoming has resulted in much confusion, including multiple orbital interpretations for a given stratigraphy (e.g., Meyers et al., 2001; Prokoph et al., 2001), and has also roused suspicion about the veracity of astrochronology (e.g., Algeo and Wilkinson, 1988; Wilkinson et al., 1996; Pietras et al., 2003). Even when rigorous quantitative spectral methods have been applied to identify significant bedding periods in strata (or modulations of these periods; Herbert, 1992; Hinnov, 2000), most studies have only evaluated the results qualitatively, by considering whether spectra appear to have a reasonable fit to an orbital model (one may ask, how good a fit is sufficient?). The results of such exercises can be quite subjective, and the errors introduced into derivative orbital time scales can be considerable, if indeed the cycles are orbitally derived.

Recent advances in signal analysis (Meyers and Sageman, 2007) provide a new approach to this problem. Specifically, orbital signal identification in the stratigraphic record can be posed as an inverse problem, where time scale uncertainty is explicitly evaluated: time is allowed to expand and contract, and the fit of the observed cycles to the predicted orbital components is quantified (also see Martinson et al., 1982 and Lisiecki and Lisiecki, 2002). The metric utilized to quantify fit is termed average spectral misfit (ASM, in cycles/k.y.; see the GSA Data Repository[1]). The ASM technique yields an objective estimate of the optimal sedimentation rate for a stratigraphic interval that preserves a record of orbital forcing. It is important that this technique provides a formal statistical test for rejection of the null hypothesis (H_o) of no orbital signal, and can be applied to untuned stratigraphic data. Because the method does not require independent time control (e.g., radiometric data), it is optimal for assessing orbital forcing in deep-time paleoclimate records.

In this study, I apply the ASM method to address two long-standing controversies about the origin of rhythmic sedimentation in strata: the Triassic Latemar Limestone (Dolomites, Italy) and the Eocene Green River Formation (Wyoming, USA). Both of these stratigraphic units are of great significance to the science of cyclostratigraphy, having served as a foundation upon which the field has developed (Bradley, 1929; Fischer, 1986; Goldhammer et al., 1987). Both cases involve controversies about the intercalibration of orbital and radiometric chronometers (e.g., Fischer and Roberts, 1991; Preto et al., 2001; Zuehlke et al., 2003; Pietras et al., 2003). I specifically investigate two important data sets that have been focal points of these Milankovitchian debates: a lithofacies data series from the Latemar Limestone (Preto et al., 2001), and Fischer Assay data from the Green River Formation (Roehler, 1991).

LATEMAR PLATFORM

The Latemar Limestone (Dolomites, Italy) is a Middle Triassic carbonate platform that formed in the western tropical Tethys Ocean (Goldhammer et al., 1987). The platform is composed of meter-scale lithologic cycles that are generally characterized by lower limestone units (weakly laminated limestones, wackestones, packstones, and grainstones) that alternate with diagenetic dolomitic caps, interpreted as reflecting submergence and emergence cycles (Goldhammer et al., 1987; Preto et al., 2001). Multiple orbital interpretations have been proposed for these lithologic cycles (Goldhammer et al., 1987; Hinnov and Goldhammer, 1991; Preto et al., 2001, 2004; Zuehlke et al., 2003; Mundil et al., 2003; Zuehlke, 2004; Kent et al., 2004). Of particular interest, one of the proposed orbital models (Preto et al., 2001) yields a time scale that is ~4 times longer than that predicted by the existing U/Pb zircon geochronology (Mundil et al., 1996, 2003; Brack et al., 1996). This discrepancy has resulted in a heated debate about the fidelity of the orbital signal versus the zircon geochronology. On the one hand, an alternative orbital model has been proposed that is consistent with the zircon geochronology (Zuehlke et al., 2003): in this model, the elementary bedding cycles that Preto et al. (2001) interpreted as precession driven (~20 k.y.) are attributed to a speculative 4.2 k.y. forcing, while the Milankovitch cycles are assigned to variability at lower frequencies. On the other hand, it has been argued that the growth history and/or geologic origin of the zircons have compromised the U/Pb chronometer (Hardie and Hinnov, 1997; Brack et al., 1997; Preto et al., 2004). In addition to the cyclostratigraphic interpretations noted above, Kent et al. (2004) proposed that the elementary cycles are due to a 1.7 k.y. forcing, based on magnetostratigraphic correlation of the Latemar Limestone to the basinal Buchenstein Beds (for an alternate interpretation, see Hinnov, 2006). Kent et al. (2004) further speculated that lower frequency variability observed in the Latemar Limestone may be attributable to Milankovitch cycles.

[1]GSA Data Repository item 2008074, additional information and seven supplementary figures, is available online at www.geosociety.org/pubs/ft2008.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

My analysis focuses on the Cimon del Latemar (CDL) lithofacies rank series of Preto et al. (2001) (Fig. DR1; see footnote 1). This data series is constructed from field observations of four basic lithofacies through the so-called Upper Cyclic Facies of the Latemar platform, and is interpreted to represent changes in relative water depth. Detailed spectral and time-frequency analyses of this record were conducted by Preto et al. (2001). In my study, multitaper method (MTM) spectral analysis of the CDL series is used to estimate power spectra, and to test for the presence of coherent sinusoids (harmonic components) in the data series (Thomson, 1982). As Figure 1B displays, most of the data variance (~80%) occurs at frequencies between 0 and 2 cycles/m, which encompasses the full range of spatial periods for which orbital forcing has been proposed. The MTM harmonic test (Fig. 1A) identifies 345 significant line components (≥90% probability) in the entire spectrum, and 61 significant harmonic components in the 0–2 cycles/m band.

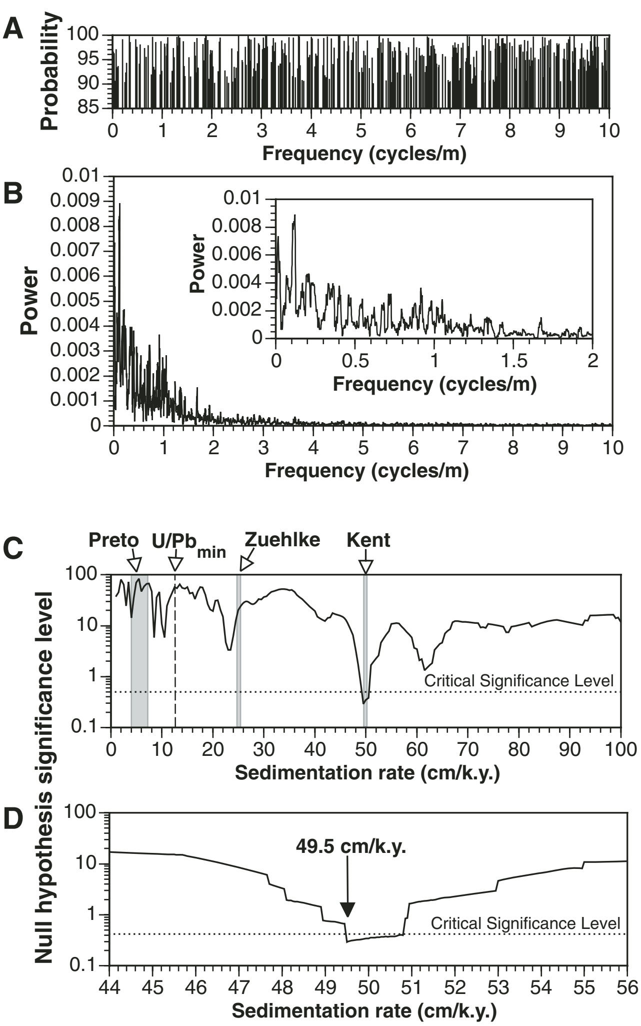

Figure 1. Multitaper method (MTM) spectral analysis and average spectral misfit (ASM) H_o significance level results for the Cimon del Latemar (CDL) lithofacies series (Preto et al., 2001). MTM spectral analysis was conducted using three 2π tapers. A: MTM harmonic analysis probability results. B: MTM power spectrum estimate. Inset displays the portion of the spectrum from 0 to 2 cycles/m. C: Null hypothesis significance levels for sedimentation rates from 1–100 cm/k.y., calculated with 0.5 cm/k.y. increment. The dotted line indicates a critical significance level of 0.503%. D: Null hypothesis significance levels for sedimentation rates from 44–56 cm/k.y., calculated with 0.05 cm/k.y. increment. The dotted line indicates a critical significance level of 0.415%. Shaded areas in Figure 1C identify sedimentation rates associated with a number of proposed time scales: Preto—range of sedimentation rates proposed in Preto et al. (2001); Zuehlke—average sedimentation rate based on the time scale proposed in Zuehlke et al. (2003); Kent—average sedimentation rate based on the time scale proposed in Kent et al. (2004). U/Pb$_{min}$—minimum sedimentation rate allowed by the zircon-based time scale (based on a 95% confidence interval; Mundil et al., 2003).

Average spectral misfit analysis of these MTM results is conducted in an iterative manner. First, a large range of plausible sedimentation rates is investigated at a relatively coarse resolution. If significant results are identified, a higher-resolution analysis is conducted over a more narrow range of sedimentation rates to refine the time scale estimate. ASM analysis across sedimentation rates from 1–100 cm/k.y. (0.5 cm/k.y. increment) is sufficient to evaluate all proposed time scales, and reveals an optimal sedimentation rate of 49.5 cm/k.y. (ASM = 7.75×10^{-4} cycles/k.y.; H_o significance level = 0.293%; Fig. 1C; Fig. DR2). This sedimentation rate is the only value that exceeds the critical significance level of 0.503% (given the analysis of 199 independent sedimentation rates, we can expect 1 value that reaches 0.503% purely by chance). In addition to a global minimum at 49.5 cm/k.y., notable local minima occur at 61.5 cm/k.y (ASM = 1.48×10^{-3} cycles/k.y.; H_o significance level = 1.330%), 23.0 cm/k.y. (ASM = 1.15×10^{-3} cycles/k.y.; H_o significance level = 3.324%), 10.5 cm/k.y. (ASM = 6.36×10^{-4} cycles/k.y.; H_o significance level = 5.910%), 8.5 cm/k.y. (ASM = 5.17×10^{-4} cycles/k.y.; H_o significance level = 5.840%), and 4.0 cm/k.y. (ASM = 3.20×10^{-4} cycles/k.y.; H_o significance level = 14.308%). Of these local minima, the 4.0 cm/k.y. result is consistent with the orbital interpretation proposed by Preto et al. (2001), and the 23.0 cm/k.y. result is nearly in agreement with the orbital interpretation proposed by Zuehlke et al. (2003).

To refine this ASM estimate, a more detailed analysis is conducted across sedimentation rates from 44–56 cm/k.y., with a 0.05 cm/k.y. increment. The calculations confirm an optimal sedimentation rate of 49.5 cm/k.y. for the Latemar Limestone (ASM = 7.75×10^{-4} cycles/k.y.; H_o significance level = 0.293%; Fig. 1D), a result that again exceeds the critical significance level. Based on this analysis we can conclude that there is only a 0.293% probability that the null hypothesis (no orbital signal) will be rejected in error. In addition, these ASM results confirm the orbital interpretation proposed by Kent et al. (2004).

The CDL lithofacies rank series reveals temporal periods consistent with all of the expected precession, obliquity, and eccentricity orbital components (Table 1, Fig. DR3). Due to the inherent resolution limitations of the CDL series, the long eccentricity component (404.18 k.y.) is not detectable, and the single observed eccentricity component (106.33 k.y.) represents a spectral average of the predicted short eccentricity periods (123.82 k.y. and 94.78 k.y.). The single observed obliquity component (37.41 k.y.) is intermediate between the predicted obliquity values (45.29 k.y. and 35.77 k.y.). Finally, the observed precession components (21.96 k.y. and 17.72 k.y.) are in close agreement with their predicted values (21.25 k.y. and 17.75 k.y.).

TABLE 1. PREDICTED AND OBSERVED PERIODS FOR THE CIMON DE LATEMAR LITHOFACIES SERIES

Observed frequency (cycles/m)	MTM harmonic probability (%)	Observed periodicity (k.y.)	Orbital interpretation (k.y.)
0.019	96.54	106.33	Eccentricity: 123.82 + 94.78
0.054	90.55	37.41	Obliquity: 45.29 + 35.77
0.092	93.31	21.96	Precession: 21.25
0.114	93.55	17.72	Precession: 17.75

Note: MTM—multitaper method. Observed temporal periods were determined using the optimal sedimentation rate identified in Figure 1 (49.5 cm/k.y.). Predicted orbital periods are from Berger et al. (1992) and Berger and Loutre (1991).

GREEN RIVER FORMATION

The Eocene Green River Formation consists of intermontane lacustrine deposits that formed in an area that now includes Utah, Colorado, and Wyoming (Bradley, 1929; Fischer, 1986). In Wyoming, the middle member of the Green River Formation (the Wilkins Peak Member) is characterized by meter-scale lithologic cycles (Fischer and Roberts, 1991; Roehler, 1993). These depositional cycles display a sequence that can be described as a succession of oil shale, trona and halite, and mudstone (Fischer and Roberts, 1991; Roehler, 1993) (more detailed descriptions were developed by Pietras et al., 2003). Numerous investigators have interpreted the lithologic rhythms as orbitally forced lake level changes (e.g., Fischer and Roberts, 1991; Pietras et al., 2003; Machlus, 2005). However, temporal calibration of the stratigraphic cycles using $^{40}Ar/^{39}Ar$ dating of interbedded tuffs (Smith et al., 2003, 2006; Machlus et al., 2004; Machlus, 2005) has yielded mixed results: the fundamental cycle can be alternatively attributed to precession, semiprecession, or a millennial-scale autocyclic origin. At the heart of this debate are concerns about the quality of the radiometric data, for example, xenocryst contamination (yielding ages that are too old) versus $^{40}Ar^*$ loss (yielding ages that are too young) (Smith et al., 2003, 2006; Machlus et al., 2004; Machlus, 2005).

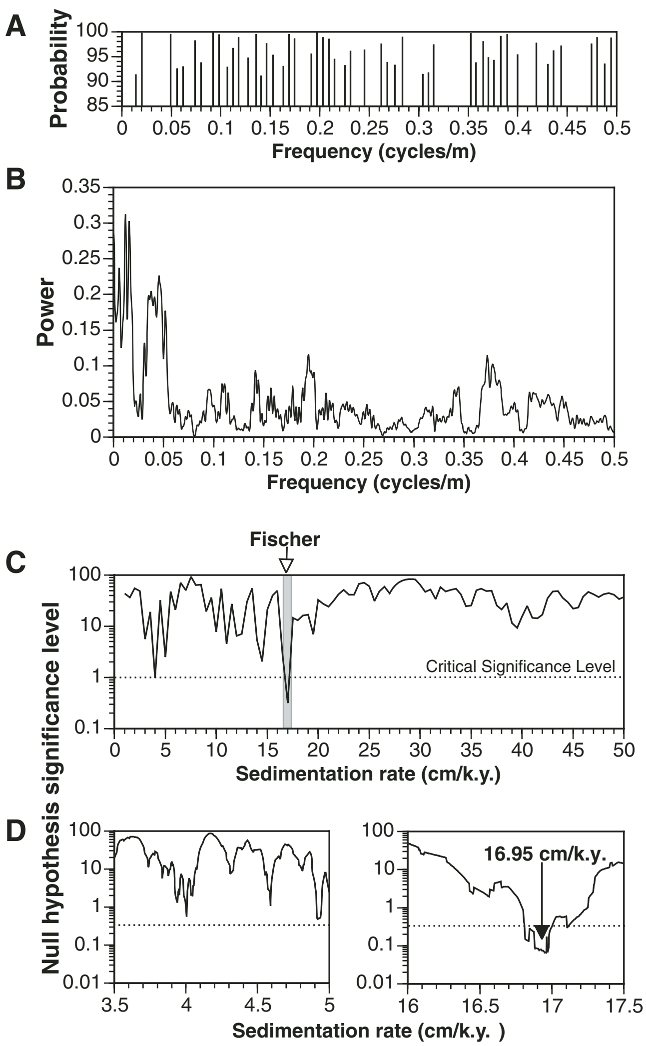

Figure 2. Multitaper method (MTM) spectral analysis and average spectral misfit (ASM) H_o significance level results for the Green River Formation CCR-1 (Currant Creek Ridge No. 1) Fisher Assay data series (Roehler, 1991). MTM spectral analysis was conducted using three 2π tapers. A: MTM harmonic analysis probability results. B: MTM power spectrum estimate. C: Null hypothesis significance levels for sedimentation rates from 1–50 cm/k.y., calculated with 0.5 cm/k.y. increment. The dotted line indicates a critical significance level of 1.010%. D: Null hypothesis significance levels for sedimentation rates from 3.5–5 cm/k.y. and 16–17.5 cm/k.y., calculated with 0.005 cm/k.y. increment. The dotted line indicates a critical significance level of 0.332%. The shaded area in Figure 2C identifies the sedimentation rate that is consistent with the orbital interpretation of Fischer and Roberts (1991) and Machlus (2005).

My analysis focuses on Fischer Assay data from the Wilkins Peak Member of the Green River Formation (Roehler, 1991) (Fig. DR1). Numerous studies have utilized Fischer Assay data (in gallons of oil per ton of rock) to investigate cyclicity within the Green River Formation (e.g., Fischer, 1986; Roehler, 1991, 1993; Pietras et al., 2003; Machlus, 2005). The basis for such investigations is a general correspondence between lithologic cyclicity (as defined above) and oil yield (Roehler, 1993; Machlus, 2005). Due to an observed decrease in cycle preservation in basin margin environments (Pietras et al., 2003), I focused my analysis on a basin center core from an expanded interval of the Wilkins Peak Member (Currant Creek Ridge No. 1, CCR-1). This record is of sufficient resolution to permit an evaluation of all proposed orbital models. Detailed spectral and time-frequency analyses of this Fischer Assay data were conducted by Machlus (2005).

MTM spectral analysis of the Fischer Assay data from CCR-1 identifies 51 significant line components (≥90% probability) in the spectrum (Fig. 2A). ASM analysis of these results across sedimentation rates from 1–50 cm/k.y. (0.5 cm/k.y. increment) is sufficient to test all proposed time scales, and yields two candidate sedimentation rates that exceed the critical significance level: 4.0 cm/k.y. (ASM = 1.77×10^{-5} cycles/k.y.; H_o significance level = 0.984%) and 17.0 cm/k.y. (ASM = 1.37×10^{-4} cycles/k.y.; H_o significance level = 0.315%) (Fig. 2; Fig. DR4). To refine this ASM estimate, a more detailed analysis is conducted from 3.5–5 cm/k.y. and 16–17.5 (0.005 cm/k.y. increment). The calculations reveal an optimal sedimentation rate of 16.95 cm/k.y. (ASM = 7.78×10^{-5} cycles/k.y.; H_o significance level = 0.065%; Fig. 2D), which again exceeds the critical significance level. Based on this analysis of the CCR-1 Fischer Assay data, we can conclude that there is only a 0.065% probability that the null hypothesis (no orbital signal) will be rejected in error. In addition, the ASM results confirm the orbital interpretation previously proposed by Fischer and Roberts (1991) and Machlus (2005). The Green River Formation CCR-1 series contains temporal periods that are in close agreement with all of the predicted precession, obliquity, and eccentricity orbital components (Table 2; Fig. DR5).

CONCLUSIONS

This study provides the first null hypothesis test for orbital forcing in the Green River Formation and Latemar Limestone. The H_o significance levels provide a baseline against which future investigations

TABLE 2. PREDICTED AND OBSERVED PERIODS FOR THE GREEN RIVER FORMATION CCR-1 FISCHER ASSAY DATA SERIES

Observed frequency (cycles/m)	MTM harmonic Probability (%)	Observed periodicity (k.y.)	Orbital interpretation (k.y.)
0.014	91.24	421.41	Eccentricity: 404.18
0.049	99.36	119.67	Eccentricity: 123.82
0.062	92.83	95.16	Eccentricity: 94.78
0.112	96.58	52.52	Obliquity: 52.10
0.146	97.52	40.32	Obliquity: 39.90
0.262	97.46	22.52	Precession: 22.60
0.315	97.27	18.73	Precession: 18.80

Note: MTM—multitaper method. CCR-1—Currant Creek Ridge No. 1. Observed temporal periods were determined using the optimal sedimentation rate identified in Figure 2 (16.95 cm/k.y.). Predicted orbital periods are from Berger et al. (1992) and Berger and Loutre (1991).

should be compared (Latemar Limestone = 0.293%; Green River Formation = 0.065%). In both cases, the procedure also identifies the most plausible average sedimentation rate that agrees with an orbital forcing model (Latemar Limestone = 49.5 cm/k.y.; Green River Formation = 16.95 cm/k.y.). These results yield astrochronologies that are consistent with proposed radio isotopic based times scales (Mundil et al., 2003; Machlus, 2005). More generally, the ASM method provides a new objective standard for orbital time scale development.

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