PERIODICITY OF MESOSCALE PHANEROZOIC SEDIMENTARY CYCLES AND THE ROLE OF MILANKOVITCH ORBITAL MODULATION[1]

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ABSTRACT

Data on more than 200 mesoscale sedimentary cycles indicate that Phanerozoic cycle periods are randomly distributed with respect to the four major Milankovitch orbital parameters, except Late Mississippian through Late Pennsylvanian cycles which show positive clustering about the 413,000 yr eccentricity period. Cycle periods, calculated from average thicknesses and accumulation rates, are strongly dependent on the former (correlation coefficient = 0.802), but relatively independent of the latter (correlation coefficient = −0.360). Hence, calculated period is largely a function of average cycle thickness, and Milankovitch-range periods will be preferentially calculated for cycles with average thicknesses between 1 m and 20 m, regardless of actual causes of cyclicity. For individual cyclic sequences, arguments for Milankovitch control based solely on average period are unfounded. Comparison of short-term Holocene sedimentation rates and long-term Phanerozoic accumulation rates for cyclic peritidal and deltaic facies suggests that average cycle deposition occurs in about 1/30 of the time represented by average cycle period. Thus, long, unconstrained intervals of non-deposition predominate in most cratonic and continent-margin cyclic sequences.

INTRODUCTION

Periodicity in sedimentary phenomena is currently the focus of much attention, an emphasis reflected both by the large number of recent papers on cyclic sequences and by two recent symposia on the subject (NATO Advanced Research Workshop, *Milankovitch and Climate,* Berger et al. 1984; Princeton University Symposium, *Cyclicity in the Milankovitch Band Through Geologic Time,* Arthur and Garrison 1986). In large measure this interest is due to an ongoing search for a stratigraphic measuring stick that will offer greater temporal resolution than is currently afforded by biostratigraphic zonation.

Mesoscale (1 to 100 m) sedimentry cycles hold particular potential in this respect, as they commonly represent depositional time intervals of thousands to hundreds of thousands of years vesus intervals of a few million years spanned by most biostratigraphic zones (Busch and Rollins 1984; Heckel 1986). A necessary premise underlying the potential usefulness of such cycles is that mechanisms controlling cycle deposition are periodic or nearly so. In addition, if such mechanisms are globally synchronous, then mesoscale cycles could also prove useful for long-distance correlations. Thus, there exists a strong incentive to attribute cycles to periodic, globally-operative processes.

The origin of sedimentary cycles has been the focus of debate since the early 19th century (De la Beche 1834; Phillips 1836, cited in Duff et al. 1967), and the challenge of explaining ordered sequences in a generally disordered stratigraphic record has produced multifarious interpretations (Wells 1960; Duff et al. 1967). Although Gilbert conceived of orbital control of sedimentary cycles as long ago as 1895, the idea did not catch on until Milankovitch (1941) quantified variations in insolation at different seasons and latitudes due to changes in the earth's orbital geometry; research beginning in the 1950's clearly established the presence of orbital periodicities in marine Pleistocene sequences (e.g., Imbrie and Imbrie 1979). Since then, the Milankovitch concept has been widely applied to ancient sedimentary cycles of most geologic periods ranging back to the Early Proterozoic (e.g., Grotzinger 1986; Olsen 1984; Schwarzacher and Fischer 1982).

The most commonly advanced argument in support of Milankovitch modulation is that the calculated average "period" in a sequence of sedimentary cycles coincides roughly with one of the four major orbital periods: the 21,000 yr precession cycle, the 41,000 yr obliquity cycle, or the circa 100,000

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stratigraphic sections are often too short, relative to mesoscale cycle thicknesses, for reliable determination of harmonic power spectra.

In general, estimates of cycle period used here have an accuracy of no better than plus or minus a factor of two (0.3 log period units), and even greater uncertainties pertain in some cases. This uncertainty derives from the fact that durations of most formations are poorly constrained and often depend on assumptions of uniform accumulation rate throughout an entire geologic epoch. In addition, durations of most geologic epochs prior to the Jurassic are still poorly known. This latter point is demonstrated by the very wide range of durations given for Paleozoic epochs in Van Eysinga (1978), Harland et al. (1982), and AAPG (1983).

Control of Cycle Period.—On the whole, Phanerozoic cycle periods are randomly distributed with respect to age (fig. 1). Most epochs exhibit a wide spectrum of cycle periods, commonly ranging from 10^4 to 10^7 years. Those having the smallest period standard deviations (represented by ten or more cyclic sequences) are the Upper Mississippian, Lower Pennsylvanian, and Upper Pennsylvanian (fig. 1). Mean periods for these epochs fall between 400,000 and 500,000 yrs, a clustering which is especially significant in light of the fact that the 50 tabulated formations representing these epochs are geographically diverse (from five continents) and record deposition in a broad range of environments (from all five settings of this study). Such clustering may well reflect orbital control of Carboniferous cycles through glacio-eustasy related to the Gondwanan Ice Age, the duration of which (Upper Mississippian to Middle Permian) is nearly synchronous with the documented range of cyclothemic deposits (Crowell 1978). Similar conclusions for other epochs with small period standard deviations (e.g., Late Cambrian and Early Ordovician) would be premature, as these are represented by six or fewer cyclic sequences from a single sedimentary environment.

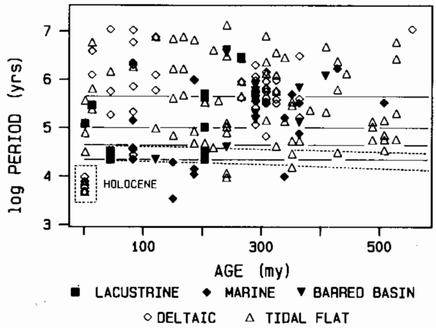

FIG. 1.—Phanerozoic barred basin, deltaic, tidal flat, lacustrine, and subtidal marine cycle periods by geologic age. Note uncapped Holocene sequences to the lower left. Present-day Milankovitch periods are shown as solid horizontal lines; presumed evolution of the precession and obliquity periods are shown as dashed lines. Phanerozoic cycle periods are distributed randomly with respect to the 21,000 yr, 41,000 yr, and 100,000 yr lines, but significant clustering of Late Paleozoic cycles occurs around the 413,000 yr line.

The distribution of Phanerozoic cycle periods relative to Milankovitch periods was evaluated by establishing four test ranges, with one Milankovitch period as the midpoint of each range (table 1). Test ranges were chosen to maximize the number of included cycles without encroaching on another test range and, hence, test range limits fall roughly mid-way between adjacent Milankovitch periods. For each Phanerozoic cycle within a test range, the absolute distance

TABLE 1

STUDENT'S "T" HYPOTHESIS TEST OF CLUSTERING OF CYCLE PERIODS AROUND MILANKOVITCH PERIODS

Period log yr	Test Range log yr	Mean log yr	St. Dev. log yr	No. Samps.	Critical Region	Test Stat.	Test Result
4.32	4.12–4.52	.096	.071	18	1.740	.240	Random
4.61	4.41–4.81	.104	.057	23	1.717	.364	Random
5.00	4.80–5.20	.107	.056	27	1.706	.648	Random
5.62	5.22–6.02	.160	.115	71	1.669	2.941	Cluster

NOTE.—Confidence interval = 95%.

from the midpoint Milankovitch period was determined. If Phanerozoic cycle periods are randomly distributed, mean absolute distance should be half the distance from range midpoint to range limits. However, if Phanerozoic cycle periods cluster about any of the four Milankovitch periods, then mean absolute distance should be less. One-way hypothesis tests (confidence level = 95%) were then performed to determine whether differences between actual and random values for mean absolute distance were significant. These indicate that Phanerozoic cycle periods are randomly distributed in relation to the 21,000 yr, 41,000 yr, and 100,000 yr Milankovitch periods, but that significant positive clustering exists about the 413,000 yr period (table 1). The source of this clustering appears to reside entirely in the large number of Late Paleozoic cycles with periods of this magnitude (fig. 1).

Whether large-scale clustering about the other three Milankovitch periods exists is uncertain. Strong positive clustering about the 413,000 yr period is based on a data set about three times larger than that for each of the shorter orbital periods. Additionally, the shorter periods have narrower test ranges in both linear and log period units, which makes a non-random result more difficult to achieve. On the other hand, uncertainty in cycle period estimates will not significantly alter the overall distribution of Phanerozoic cycle periods, as inaccuracy in period estimates by a factor of two only gives rise to an error of 0.3 in log period units (fig. 1). Significantly, cycle periods occur with equal frequency from 21,000 yr to 413,000 yr (the Milankovitch range) and from 500,000 yr to 10,000,000 yr for most geologic epochs. This distribution reveals no tendency for cycle periods to fall preferentially in the Milankovitch range and suggests that non-Milankovitch mechanisms may be important in the formation of Phanerozoic cycles at all periodicities.

Theoretical changes in the Milankovitch orbital periodicities during the Phanerozoic do not alter these results. As the 100,000 yr and 413,000 yr eccentricity periods are the product of interplanetary gravitational forces, they have probably remained stable through at least the last 600 m.y. (Walker and Zahnle 1986). On the other hand, the 21,000 yr precession and 41,000 yr obliquity periods

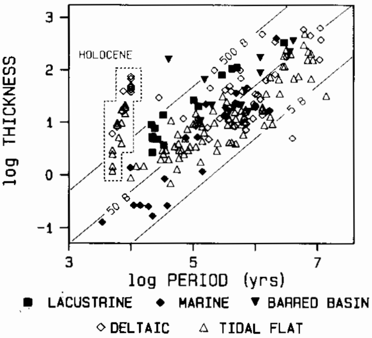

FIG. 2.—Average periods for all Phanerozoic cycles in figure 1 versus average cycle thicknesses. Equal sedimentation rates plot as diagonal lines from lower left to upper right across diagram. The three lines represent, from upper left to lower right, the mean pre-Holocene sedimentation rate times one order of magnitude (500 B), the mean rate (50 B), and the mean rate divided by one order of magnitude (5 B). Note that 98% of all pre-Holocene cycles fall within one order of magnitude of the mean sedimentation rate. Uncapped Holocene sequences occupy the dashed field.

have changed due to continued evolution of the earth-moon system (Lambeck 1980). Transfer of angular momentum to the moon has resulted in a decrease in the earth's rotational velocity and an increase in the moon's orbital velocity. The consequent recession of the moon has resulted in attenuation of the periods of the Earth's precession and obliquity cycles. Approximation of orbital paleoperiods (Walker and Zahnle 1986) indicate that the period of precession was about 17,000 yrs and that of obliquity about 28,000 yrs at the beginning of the Phanerozoic. Testing cycle periods in a range defined around evolving precession and obliquity periods also indicates a random distribution (fig. 1).

Control of Cycle Thickness.—Because cycle periods are not measured directly but are calculated from cycle thicknesses and sedimentation rates, their distribution is dependent on the latter two parameters. Phanerozoic cycle periods have a strong positive correlation with thicknesses (correlation coefficient = 0.802) but only a weak negative correlation with sedimentation rates (correlation coefficient = −0.360). Hence, average cycle thickness is the best predictor of average cycle period, while variation in sedimentation rate at any given thickness gives rise to variance in cycle period (fig. 2). The nar-

TABLE 2

Example of Calculated Cycle Periods

Sed. Rate (B)	Cycle Thickness (m)				
	1	3.2	10	32	100
420	2	8	24	75	240
138	7	23	72	230	720
47	22	68	220	680	2,200
15	65	210	650	2,000	6,500
5.2	200	620	1,900	6,200	19,000

Note.—Cycle periods in thousands of years.

rowness of the range of observed accumulation rates is shown by the fact that 98% of all Phanerozoic cycle accumulation rates fall between 5 B and 500 B (1 Bubnoff = 1 m/m.y.) and thus span just two orders of magnitude. The significance of this constraint is that cycles of any given thickness must yield periods within a limited range, regardless of the actual mechanism of cycle formation.

The range of calculable mesoscale cycle periods is shown by table 2, in which periods are determined for representative values of average cycle thickness and sedimentation rate. Thicknesses were chosen from 1 m to 100 m (0 to 2 log m) at 0.5 log m increments, while sediment accumulation rates were selected from 5.2 B to 420 B (0.71 to 2.62 log B) at one standard deviation increments based on the average accumulation rate (1.67 log B) and standard deviation (0.48 log B) for all pre-Holocene cycles. Phanerozoic cycle accumulation rates are roughly log-normally distributed so that, at any given thickness, the calculated period of 68% of the cycles will be within one standard deviation of the mean accumulation rate and 95% within two standard deviations (table 2). For cycles of certain thicknesses, there is a strong probability of calculating a period in the Milankovitch range. For example, for 1 m to 20 m cycles this probability exceeds 50%; for 5 m cycles it is greater than 90%. This relationship indicates that, given average Phanerozoic sediment accumulation rates, cycles genuinely deposited under Milankovitch control will most commonly be between 1 m and 20 m thick.

The converse, that most cycles between 1 m and 20 m in thickness were deposited under Milankovitch control, is almost certainly not true. The generation of meter-scale cycles is characteristic of many systems in which intrinsic factors (such as spatially variable sediment production or dispersal) predominate. Examples of such (almost purely autocyclic) processes include cycles produced through channel migration in fluvial and alluvial fan systems, and deltaic lobe-switching (Walker 1984; Reading 1986). Even if allocyclic mechanisms can be clearly demonstrated as having been important during the accumulation of a group of cycles, a Milankovitch origin is by no means proven, or even implicated, solely on the basis of average cycle thickness or estimated period. Processes other than orbitally-modulated sea level and/or climatic change may also operate with quasi-periods in the Milankovitch range (e.g., Cisne 1986).

Control of Sedimentation Rate.—Despite the narrow range of long-term accumulation rates observed for Phanerozoic cycles (fig. 2), short-term sedimentation rates (during the actual deposition of any single cycle) were not necessarily similar in magnitude, nor constant through time. With respect to global sedimentary sequences, Sadler (1981) has demonstrated that short-term rates may be up to six orders of magnitude greater than long-term rates. The progressive convergence of short-term sedimentation rates to those of long-term accumulation (which is ultimately constrained by long-term rates of basin subsidence) reflects the local episodicity of global sediment accumulation and the presence of longer hiatuses in longer stratigraphic sequences.

An estimate of the ratio of depositional to non-depositional time for Phanerozoic mesoscale cycles can be obtained by comparing pre-Holocene tidal flat and deltaic cycles and lithologically identical but stratigraphically "uncapped" Holocene analogues. Although continued compaction will thin Holocene cycles somewhat, thickness ranges are very similar for environmentally equivalent ancient and modern cycles, but dissimilar for different environments regardless of sequence age (fig. 3). However, Holocene sedimentation rates (average = 3.30 log B) are more than 1.5 orders of magnitude (about 30 times) greater than pre-Holocene rates (average = 1.67 log B) for all environments (fig. 2). This difference apparently reflects the fact

precision of available data because, as mentioned earlier, estimates of cycle period have an accuracy of no better than a factor of about two. A significant degree of overlap exists between periods determined for the two sedimentary systems, and it is only the presence of a significant number of relatively thin tidal flat cycles that gives rise to different average periods and accumulation rates (fig. 4). Further, while eon-average cycle parameters may reveal broad trends associated with specific environments, it is also necessary to consider epoch-specific changes in frequency and periodicity of cyclic sea level oscillations through the Phanerozoic in order to draw firm genetic inferences. Detailed study of cycle thicknesses, periods, and accumulation rates among different depositional systems and geologic periods may ultimately help to resolve questions of autocyclicity versus allocyclicity and globality versus regionality in the processes of episodic sediment accumulation.

DEMONSTRATION OF MILANKOVITCH ORBITAL MODULATION

If, in fact, a calculated average period within the broad range of Milankovitch periodicities is not a sufficient test of orbital modulation of sedimentary cycles, demonstration of such control becomes significantly more difficult than hitherto appreciated. As a prelude to the advancement of any orbital mechanism of sedimentary cycle formation, it is first necessary to establish that the dominant genetic factors are: (1) allocyclic rather than autocyclic in nature, and (2) climatic or eustatic (short-term variations of which are climatically controlled) rather than tectonic.

The inherent difficulty of this task is well-illustrated by Grotzinger's (1986) excellent study of cyclicity in the Precambrian Rocknest Formation, in which he advocated both Milankovitch-modulated glacio-eustasy and non-uniform rates of deposition as the primary controls on the formation of upward-shoaling peritidal carbonate cycles. As in this case, most advocates of Milankovitch-modulated cyclic sedimentation have relied on short-term changes in global sea level as the primary causative agent of episodic sediment accumulation. Various arguments concerning cycle asymmetry, continuity, and composition as records of sea level change and subaerial exposure are commonly offered in support of such interpretations.

However, in a context of demonstrating Milankovitch-modulated control of cycle formation, arguments based on cycle asymmetry and apparent rapidity of transgression are largely irrelevant. Cycle asymmetry is characteristic of most sedimentary cycles and does not require an asymmetric mechanism of eustatic change such as continental ice sheet growth (Read et al. 1986), and rapidity of flooding cannot be uniquely determined from such sequences because the stratigraphic record of transgression reflects both rates of flooding and rates of sediment accumulation (Carozzi 1986). Arguments for eustatic control based on subaerial exposure and meteoric vadose diagenesis of cycle tops do not distinguish between allocyclic and autocyclic mechanisms of exposure in that facies progradation and meteoric diagenesis of Holocene tidal flats are occurring under nearly stable sea level conditions (e.g., Bush 1973; Brown and Woods 1974) and are thus not diagnostic of sea level falls. On the other hand, arguments based on incomplete shoaling within cycles and vadose caps on subtidal units support an allocyclic mechanism (e.g., Goldhammer et al. 1987), even though stratigraphic breaks may result from factors other than eustasy, such as from local tectonic movements (Cisne 1986), regional epeirogeny (Harrison et al. 1981), or geoidal migration (Moerner 1976). In essence, interpretation of lithologic data is generally ambiguous and inconclusive with respect to determination of controls on cycle formation.

Apart from average cycle periodicity and lithologic features, the most commonly cited line of evidence for Milankovitch control is the demonstration of a hierarchy of cycles in which: (1) the recurrence ratio of subordinate to superior cycles correspond to one of the ratios between periods of the dominant orbital parameters, and (2) the calculated periods correspond approximately to those of the anticipated orbital parameters (e.g., Goldhammer et al. 1987; Grotzinger 1986; Heckel 1986). Thus, modulation by the precession and short eccentricity cycles is inferred for a sequence comprising two orders of cycles with a recurrence ratio of 5:1 and calculated periods in the vicinity of 20,000 and 100,000 yrs. Cycle hierarchies can be based on variations either in a single parameter such as cycle thickness (Goldhammer et al. 1987), lithofacies ratios (Aitken 1978), or transgression maxima (Heckel 1986), or in two or more independent parameters such as shoaling cycles within alternating sedimentation regimes (Olsen 1984).

For several reasons, cycle hierarchies must be identified and interpreted with caution. First, some criteria may be unsuitable and lead to recognition of spurious higher/lower order cycles. One of the hazards of using features as subtle as bedding planes within lithologically homogeneous units was manifested in Schwarzacher's (1954) study of the Alpine Dachstein Formation, in which on average limestone-dolostone couplets comprised 4.6 beds on southern slopes, but 7.1 beds on northern slopes, a difference apparently induced by stronger weathering of northward facing sections. Second, where different orders of cycles are based on subdivision of a continuum (e.g., cycle thickness) but are treated discretely, subjective modification of subdivision partitions or of temporal ratios assigned to subdivisions can significantly influence results (e.g., Heckel 1986). Third, six different ratios (2.0, 2.5, 4.0, 5.0, 10.0, 20.0) can be produced from pairs of the four major orbital periods. Although five is the most likely, and indeed the most commonly reported, ratio due to forced modulation of the 21,000 yr precession cycle by the 100,000 yr eccentricity cycle, it should be noted that the spread of available ratios makes them difficult to miss. These problems must be addressed in advocating Milankovitch control based on multi-order cycle hierarchies.

CONCLUSIONS

What, then, can be concluded from relationships between thickness, period, and accumulation rate data on Phanerozoic mesoscale cycles? Long-term accumulation rates span a relatively narrow range, with 98% falling within an order of magnitude of the mean rate. As a consequence, calculated cycle period is largely a function of average cycle thickness, and mesoscale cycles from 1 m to 20 m will generally produce values in the Milankovitch range (21,000 yrs to 413,000 yrs). As cycles of similar thickness can be produced by mechanisms independent of orbitally-modulated climatic change, average periodicity in the Milankovitch range is not sufficient to demonstrate Milankovitch orbital control of cycle formation. Short-term sedimentation rates from "uncapped" Holocene cycles suggest that cycles are generally deposited in a small fraction of their average periods, and that most time in cyclic sequences is represented by sedimentation gaps. Cycles deposited in different sedimentary environments exhibit fundamental differences in distributions of thickness, sedimentation rate, and average period suggesting that universalistic mechanisms such as global sea level change may be inappropriate for many cyclic sequences.

Which depositional environments are most likely to display sedimentary cycles formed under Milankovitch control? Undoubtedly, the best hope of unequivocal identification of orbital climatic forcing is afforded by tectonically stable and climatically sensitive lacustrine and barred basinal systems in which varves are preserved and provide a built-in geochronometer. In contrast, paralic systems (e.g., deltas and tidal flats) are generally unsuitable because the record of long-period climatic and/or sea level changes are partially or totally obscured by other factors. Such factors include autocyclic fluctuations in sediment production and/or supply, local changes in rates of subsidence, and vagaries in sediment deposition and preservation in higher-energy environments.

Which epochs in geologic history are most likely to favor Milankovitch modulation of sedimentary cycles? In view of the voluminous data demonstrating the presence of orbital periods in Late Tertiary and Quaternary sedimentary sequences, and their correlation with ice volume changes, the answer must be epochs in which ice ages occurred. The association of Late Paleozoic continental glaciation with wide-spread cyclicity in which periods cluster strongly about one orbital parameter supports this conclusion. In the absence of a clearly defined mechanism for translation of orbital variations into cyclic sedimentation during non-glacial epochs, such control cannot be assumed, regardless of the average periods present in coeval cyclic sequences.

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