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Aperiodic accumulation of cyclic peritidal carbonate

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ABSTRACT

Tabulation of thickness data on nearly 3000 Proterozoic and Paleozoic peritidal carbonate cycles indicates that metre-scale facies associations exhibit exponential thickness frequency distributions. Because carbonate deposition occurs during infilling of available space between sea level and the surface of the preceding cycle, and because the rate of generation of accommodation space is ultimately determined by rates of platform subsidence, thicknesses of individual cycles must record the duration of time since deposition of underlying units. Exponential thickness distributions therefore require either that upward-shoaling carbonates record aperiodic accumulation, or that any periodic forcing manifest during sedimentation has been masked by the vagarious nature of depositional processes. Such a conclusion is contrary to interpretation of such carbonate units as originating from high-frequency eustatic change. In addition, exponential thickness distributions and sequence thickness structures are replicated when assuming a random probability of carbonate deposition under conditions of constant subsidence. The nature of cycle thickness distributions therefore invalidates virtually any endeavor to derive an average depositional period from mean cycle thicknesses, and refutes the use of such estimates as proxy records of past sea-level oscillation frequency, whether they are related to Milankovitch-band climate forcing or to any other periodic process.

INTRODUCTION

Construction of a high-resolution chronostratigraphic framework upon which to determine rates of geologic processes has long been a goal of stratigraphers and sedimentary geologists. Moreover, the presence of upward-shoaling metre-scale facies associations has made shallow-water carbonate sequences particularly attractive in this regard; over the past decade numerous field and modeling studies have employed cyclic marine sequences as a chronometer from which to construct such a temporal stratigraphic framework (Anderson and Goodwin, 1990; Goldhammer et al., 1987, 1990; Goodwin and Anderson, 1985; Koerschner and Read, 1989; Osleger and Read, 1991; Read and Goldhammer, 1988). These efforts have led to development of a scenario of recurrent cycle generation in response to periodic sea-level change, a cognizance of episodic carbonate accumulation that has become fully integrated with related perceptions as to the relative importance of eustatic variation in sequence stratigraphy (Vail et al., 1977; Posamentier et al., 1988; Posamentier and Vail, 1988).

This scenario holds that sequences of cyclic beds are the products of extrabasinal forcing, the frequency of which is generally calculated from cycle thickness data through use of various statistical techniques. Moreover, such efforts have determined that mean cycle frequencies are generally equivalent to Earth orbital periodicities. On the basis of this similarity, workers have concluded that metre-scale cycles owe their origin to Milankovitch-driven eustatic change (Bond et al., 1991; Goldhammer et al., 1987, 1990, 1991; Osleger and Read, 1991).

CYCLICITY AND PERIODICITY

Vertical repetition of sedimentary facies within carbonate sequences is a common depositional motif of cratonic rocks of all ages. Cyclic carbonate units reportedly consist of gradual upward transitions from relatively deep to relatively shallow water facies associations separated by abrupt contacts between shallow- and deep-water facies of the following cycle. Upward shoaling is interpreted to record the repeated episodic filling of available accommodation space.

Relations between the vertical dimension of peritidal cycles and secular periodicity during their accumulation stems from the fact that over the long term, rates of generation of accommodation space must equal rates of basin subsidence, a process taken to be relatively constant at the (few million years) time scales considered (e.g., Read and Goldhammer, 1988; Goldhammer et al., 1987, 1990). If cyclic repetition of carbonate facies in space is also periodic in time, then the average amount of accommodation space filled during the deposition of each cycle should be equal to the product of subsidence rate and periodicity of accumulation. Moreover, because rates of carbonate deposition in modern shallow-water settings are several orders of magnitude faster than rates of basin subsidence (Anders et al., 1987; Sadler, 1981; Schlager, 1981; Wilkinson et al., 1991), episodic creation of accommodation space is typically considered as being augmented through periodic sea-level change. The thicknesses of carbonate cycles formed under conditions of periodic eustatic forcing should be directly related to the frequency of sea-level change during their accumulation.

THICKNESS FREQUENCY DISTRIBUTIONS

It has been noted that the distribution of sedimentary-bed thicknesses, including carbonate cycles, is apparently unimodal and positively skewed (e.g., Davis, 1986; Krumbein and Graybill, 1965; Schwarzacher, 1975). If a logarithmic transformation of bed thickness is used, such distributions take on the shape of a normal distribution; traditionally, such conversion is accomplished to reduce skewness and facilitate comparison with the normal distribution. Although lognormal populations are common in natural systems (Ahrens, 1954; Crowley et al., 1986; Friedman, 1962; Power, 1992; Putz, 1952; Wertz, 1949), little effort has been made to understand the origin of such distributions in cyclic sequences, or to determine if alternate mathematical expressions are equally representative.

Measured sections of cyclic carbonate sequences from the Paleoproterozoic Rocknest Formation in northwest Canada (Grotzinger, 1986) and from Cambrian and Ordovician sequences of North America (Koerschner and Read, 1989; Montanez and Osleger, 1993; Osleger and Read, 1991, 1993; Read and Goldhammer, 1988) yield extensive data on the thickness of component cycles. Moreover, like cycle thicknesses reported for the Middle Triassic Latemar buildup in northern Italy reported by Hinnov and Goldhammer (1991), both Proterozoic and Phanerozoic data may be recast as lognormal frequencies (Fig. 1, insets). However, both data sets also comprise nearly ideal exponential thickness frequency distributions wherein cycles thinner than a few decimetres are increasingly underrepresented (Fig. 1, A and B). Similar distributions occur at the scale of individual stratigraphic sections as well as entire basins of deposition, and thus are independent of local or regionally controlled parameters such as subsidence rate. The lognormal appearance of either group reflects a relative absence of units thinner than the modal frequency within each population, thinner than 2.4 m among Proterozoic units and thinner than 0.45 m within Phanerozoic cycles. It is

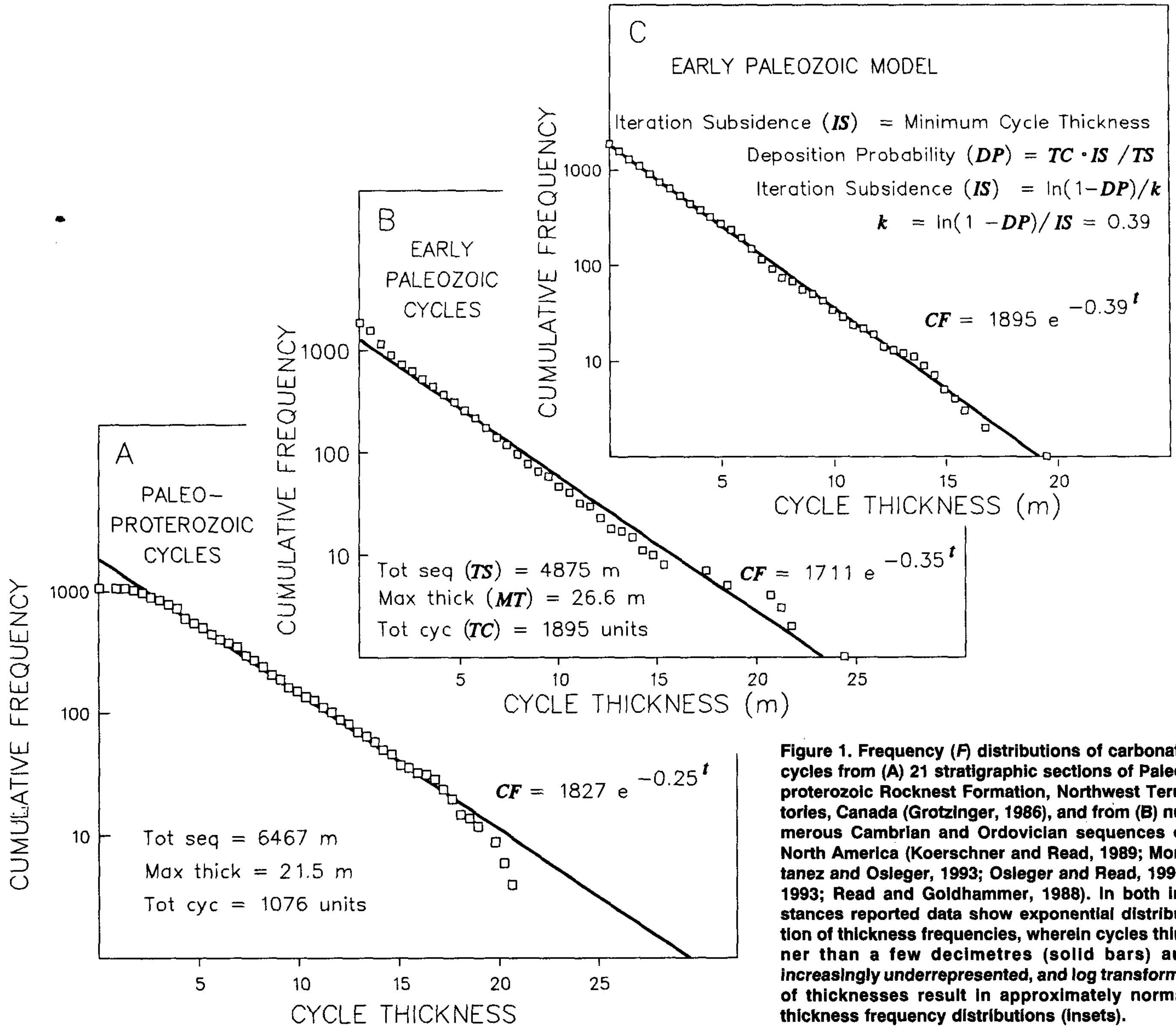

Figure 1. Frequency (*F*) distributions of carbonate cycles from (A) 21 stratigraphic sections of Paleoproterozoic Rocknest Formation, Northwest Territories, Canada (Grotzinger, 1986), and from (B) numerous Cambrian and Ordovician sequences of North America (Koerschner and Read, 1989; Montanez and Osleger, 1993; Osleger and Read, 1991, 1993; Read and Goldhammer, 1988). In both instances reported data show exponential distribution of thickness frequencies, wherein cycles thinner than a few decimetres (solid bars) are increasingly underrepresented, and log transforms of thicknesses result in approximately normal thickness frequency distributions (insets).

arguable that if these carbonate cycles can be shown to have a distinct modal thickness frequency, then that thickness interval may represent a sedimentary response to some forcing periodicity. Alternatively, carbonate cycles may in fact have exponential thickness frequencies wherein narrow beds are unrecognized and/or unrecorded in measured sections. If so, constraints imposed by relations of sediment generation and accumulation require that time intervals between depositional events are also exponentially distributed and therefore aperiodic. Three points lead us to interpret observed lognormal distributions as the product of biased sampling of a naturally occurring exponential distribution.

First, exponential distributions of many scalar parameters are abundant within natural systems, such as amounts of rainfall and magnitudes of temperature change in daily, monthly, and yearly time spans. Similarly, turbidite thickness data exhibit exponential distributions (McBride, 1962; Walker and Sutton, 1967; Hsü, 1983; Lowery, 1992), although it is not yet unequivocal if these are best linearized in thickness-log frequency or log thickness–log frequency space. Although the abundance of exponential processes and products (Mandelbrot, 1983) in Earth surface systems makes no forceful comment as to the specific nature of carbonate-cycle thicknesses, such distributions certainly comprise an extraordinary number of geologic phenomena.

Second, it is our contention that the lognormal distribution exhibited by cycle thickness data is largely an artifact of recording processes that unavoidably or inadvertently introduce a strong bias against the recognition of thin peritidal cycles. Such a bias is likely the result of a reluctance to designate thin but upward-shoaling facies associations as discrete genetic units. The nature of this thin-cycle bias becomes apparent when examining vertically dipping units within the Cambrian Conococheague Formation exposed near Wytheville, Virginia. There, as carefully reported by Koerschner and Read (1989), most cycles begin as thrombolitic to digitate boundstone or flaser-bedded "ribbon rock" (Demicco, 1983) that passes upward toward cycle-top cryptalgal laminites. The general rarity of distinct lithologic contrast between distal and proximal facies causes some difficulty in defining cycles precisely, but a much greater problem arises from the fact that progression from thick to thin cycles occurs primarily with the loss of deeper water facies (e.g., Koerschner and

Read, 1989). This results in nearly complete gradation between conspicuous upward-shoaling units with well-developed tidal-flat-over-subtidal facies, and layers a few decimetres thick of laminite over flaser bedding that only equivocally could be interpreted as cyclic, and centimetres-thick layers of peritidal laminite recording nearly invariant water depths. The net result of cycle thinning by progressive loss of distal lithologies is that, at a decimetre to centimetre scale of observation, upward shoaling cannot be demonstrated or even inferred; thus, by necessity when defining cycles, thinner peritidal layers are incorporated into the tops of underlying cycles. Such artificial amalgamation of what indeed may comprise discrete depositional events truncates the thin-cycle end of the exponential distribution, thereby producing the lognormal character.

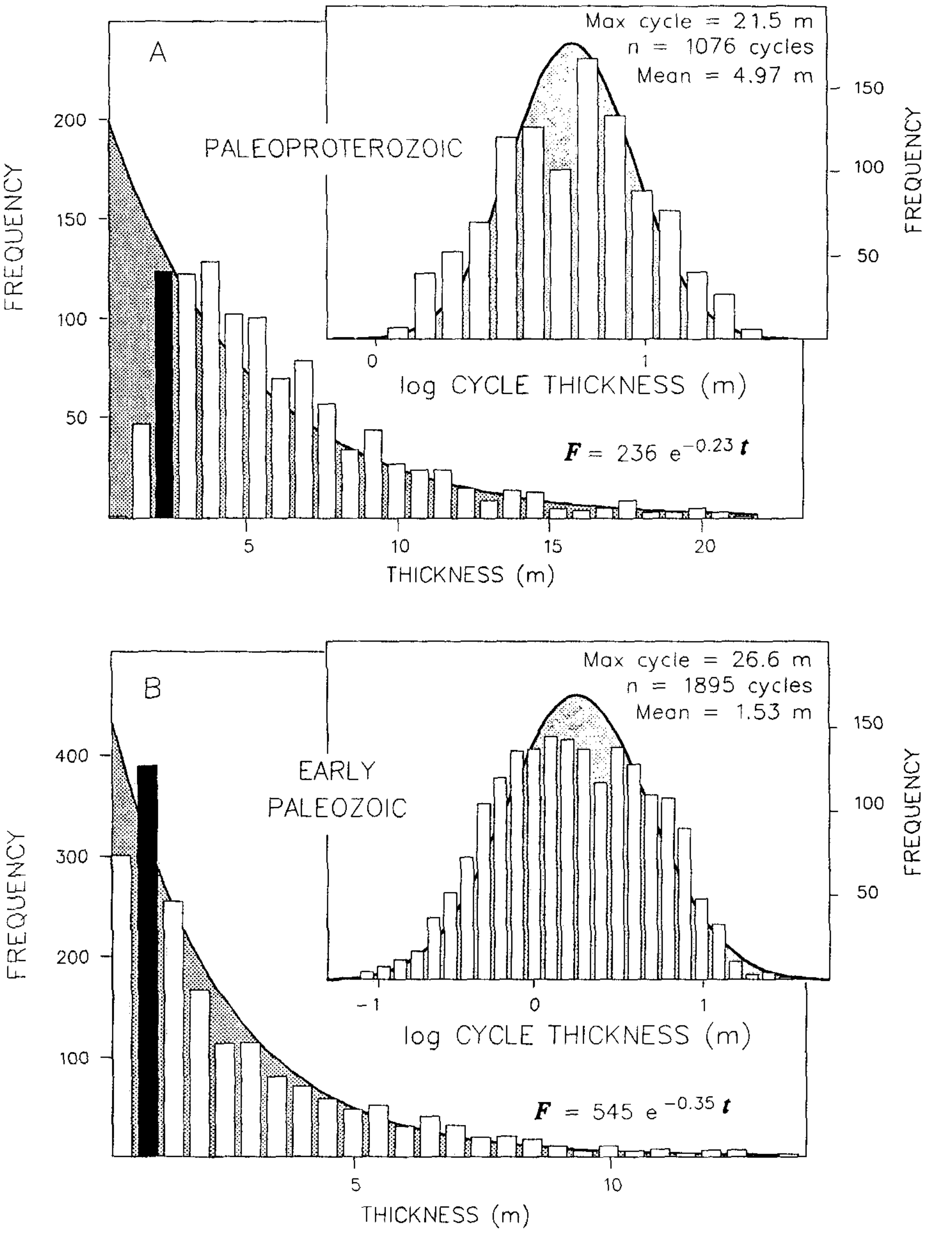

Figure 2. Cumulative frequency (*CF*) distributions of Paleoproterozoic (A) and early Paleozoic (B) cyclic carbonates (as in Fig. 1). Note that exponential constant for Paleoproterozoic cycles (−0.25) is smaller than that for Paleozoic units (−0.35), reflecting greater uniformity of cycle thicknesses among Proterozoic population. C: Cumulative distribution of theoretical cycles generated when assuming constant subsidence, some probability of deposition during each model iteration, and complete filling of available accommodation space when deposition occurs. Iteration continued until number of cycles generated equaled population of Paleozoic cycles; because estimates of aggregate sequence thicknesses and durations are known, model values of iteration subsidence (minimum reported cycle thickness) and probability of accumulation ([total cycles · iteration subsidence]/total sequence thickness) yield trends in cumulative frequency (C) that are identical to those reported from natural sequences (B).

Third, even though Cambrian exposures near Wytheville, Virginia, may be an atypical example of cycle differentiation, it is equally likely that the very exercise of measuring section in "cyclic" sequences causes underrepresentation through amalgamation of thin but genetically equivalent beds. That "metre-scale" as a describer is frequently applied to such units suggests a bias in the recognition of all such facies associations, regardless of size or origin.

EXPONENTIAL DISTRIBUTIONS

If thicknesses of peritidal carbonate cycles in fact represent a sampling bias of exponential thickness frequency distributions, what does the real thickness structure tell us about carbonate deposition, other than the fact that depositional episodes are not evenly distributed in time? To generate an answer, a simple stochastic model of cyclic sediment accumulation was formulated, the results of which closely emulate available thickness data (Fig. 2C). Under conditions of invariant sea level and constant rate of subsidence, we presume that sedimentation fills all accommodation space whenever the value of a continuous uniform random variable exceeds a prescribed probability for cycle accumulation. By specifying only the probability of deposition and rate of subsidence, an exponential distribution of cycle thicknesses is generated, much in the manner that successive coin flips result in an exponential relation between number of flips and number of consecutive heads or tails. Moreover, subsidence rate and deposition probability can be scaled to parameters from any real-world cyclic sequence. Specifically, if the amount of subsidence per model iteration (*IS*) is taken as the thinnest cycle in any sequence, and if the probability of deposition (*P*) is taken as: $P =$ (number of cycles in a sequence · *IS*)/(total sequence thickness), and if the number of model iterations equals the number of cycles divided by the probability of deposition, the resultant cumulative thickness frequency is virtually identical to that of the cyclic sequence (Fig. 2, B and C).

Although such relations appear incompatible with a scenario of periodic cycle deposition, they are in complete agreement with a perception of rapid but stochastic carbonate deposition in settings of generally invariant subsidence rate. Moreover, we emphasize that theorization of random cycle accumulation is decidedly not in dispute (or in concurrence) with presumed periodicity among groups of cycles. A characteristic of some cyclic sequences is the presence of a stacking hierarchy, wherein a pattern of thicknesses is repeated throughout a sequence. Such patterns have been interpreted as evidence for an orbitally forced origin of individual cycles (Goldhammer et al., 1987, 1990; Osleger and Read, 1991). In this context, the determination of periodicity from bed-thickness data can only be established statistically by time-series analysis of thickness variance with stratigraphic position, and any representation of thickness vs. abundance alone cannot reveal whether groups of cycles occur with any periodicity. Although exponential thickness distributions argue for aperiodic accumulation, this need not negate the possibility that cyclic sequences in rare cases may also exhibit order.

Much in the fashion of Mann (1970), who cautioned that "Cyclic sedimentation, which so long has been construed as an obviously deterministic phenomenon, in fact may not be," it is our contention that thickness distributions of shallow-water carbonate cycles are incompatible with models of periodic deposition, and probably record stochastic processes of sediment accumulation. The possibility that periodic sea-level change could result in a series of beds with an exponential thickness distribution has yet to be demonstrated or even considered by proponents of eustatic forcing. In light of available relations, we conclude that most if not all metre-scale carbonate cycles formed in a random manner independent of any periodic extrabasinal process or mechanism. Exponential thickness-frequency distributions suggest strongly that peritidal carbonate cycles are in fact aperiodic.

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