Time partitioning in cratonic carbonate rocks

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ABSTRACT

Dissimilarity in relations between thickness, duration, and accumulation rate in Holocene sections, metre-scale Phanerozoic cycles, and epoch-interval Phanerozoic sequences reflects variation in the distribution of depositional and hiatal time at different scales of observation. Modern accumulation rates are strongly dependent on duration of deposition; lower rates correspond to longer durations. Phanerozoic cycle thicknesses are similar to those of Holocene sections, suggesting that both formed while filling similar amounts of accommodation space. However, accumulation rates of Phanerozoic cycles and sequences are about two orders of magnitude less than in modern settings, and they show neither strong dependence on duration of accumulation nor significant variation over Phanerozoic time. Hence, net accumulation is primarily controlled by regional subsidence rate. These relations also allow for determination of that fraction of cycle period recorded as rock and that corresponding to hiatal time at intercycle boundaries. Depending on subsidence rate and amount of compaction, most cratonic carbonate units accumulated over 3% to 30% of the time represented by sequences in which they occur.

INTRODUCTION

Several approaches have been undertaken in order to shed light on the origins of metre-scale cycles and to quantify magnitudes of sediment accumulation, subsidence, and sea-level change during carbonate deposition. One group of studies (Anders et al., 1987; Sadler, 1981) has focused on durations of depositional and hiatal time in sedimentary sequences and, in so doing, have attempted to evaluate stratigraphic "completeness" of the rock record. A closely related area of investigation (Koerschner and Read, 1989; Goldhammer et al., 1987; Grotzinger, 1986) has considered origins of upward-shallowing carbonate cycles through incorporation of various estimates of subsidence, sea-level change, and accumulation rate into iterative calculation of hypothetical stratigraphic columns and cross sections. These efforts have resulted in apparent agreement between synthetic sequences and those observed in the real world. However, the number of incorporated variables necessary for such simulations (subsidence rate, amplitude and period of sea-level change, magnitude and depth dependence of sediment generation, amount and distance of lateral transport) exceeds the number of parameters for which adequate data have been tabulated. The under-determined nature of such forward models therefore results in similar but nonunique scenarios of cycle generation. In order to

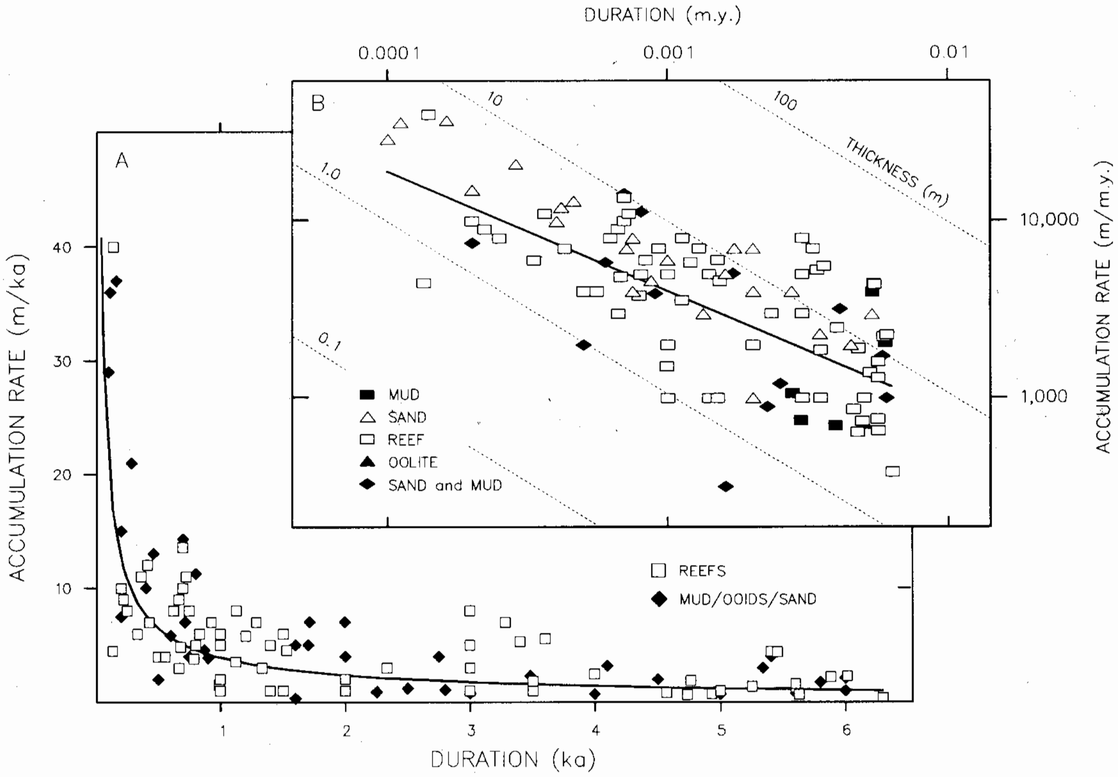

Figure 1. Carbonate accumulation in modern settings. A: Vertical accumulation rates of Holocene sediment relative to duration of deposition. B: Same Holocene data at log-scale, million-year values; thickness as diagonal lines. Note that accumulation rate is strongly dependent on duration.

better constrain patterns of shallow-water carbonate deposition, representative values of sediment-accumulation rate in modern environments, ancient cyclic sections, and ancient epoch-interval sequences have been determined from thickness and duration data; these values serve to limit choices among several alternative models of cyclic sediment accumulation in shallow-water cratonic settings.

ACCUMULATION RATES

Tabulation of 142 measurements of Holocene thickness and duration yields a trend wherein accumulation rate (A) is strongly dependent on duration (D):

$$\log A_{(\mathrm{m/m.y.})} = -0.7 \log D_{(\mathrm{m.y.})} + 1.6,$$

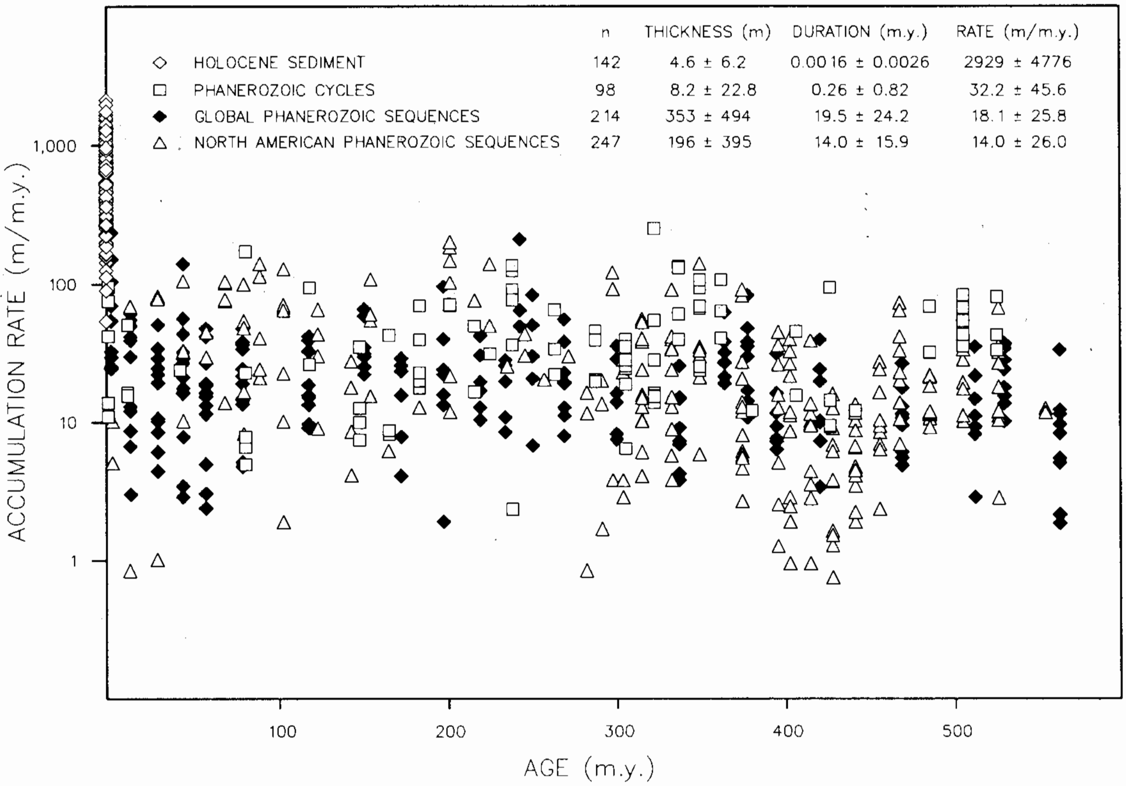

Figure 2. Holocene and Phanerozoic carbonate accumulation rates. Metre-scale cycle data from Algeo and Wilkinson (1988); North American sequence rates from data in Cook and Bally (1975); global sequence rates from Ronov (1980). Note that Phanerozoic rates define relatively narrow range of values, that these exhibit little long-term temporal change, and that all are considerably lower than accumulation rates typical of modern settings.

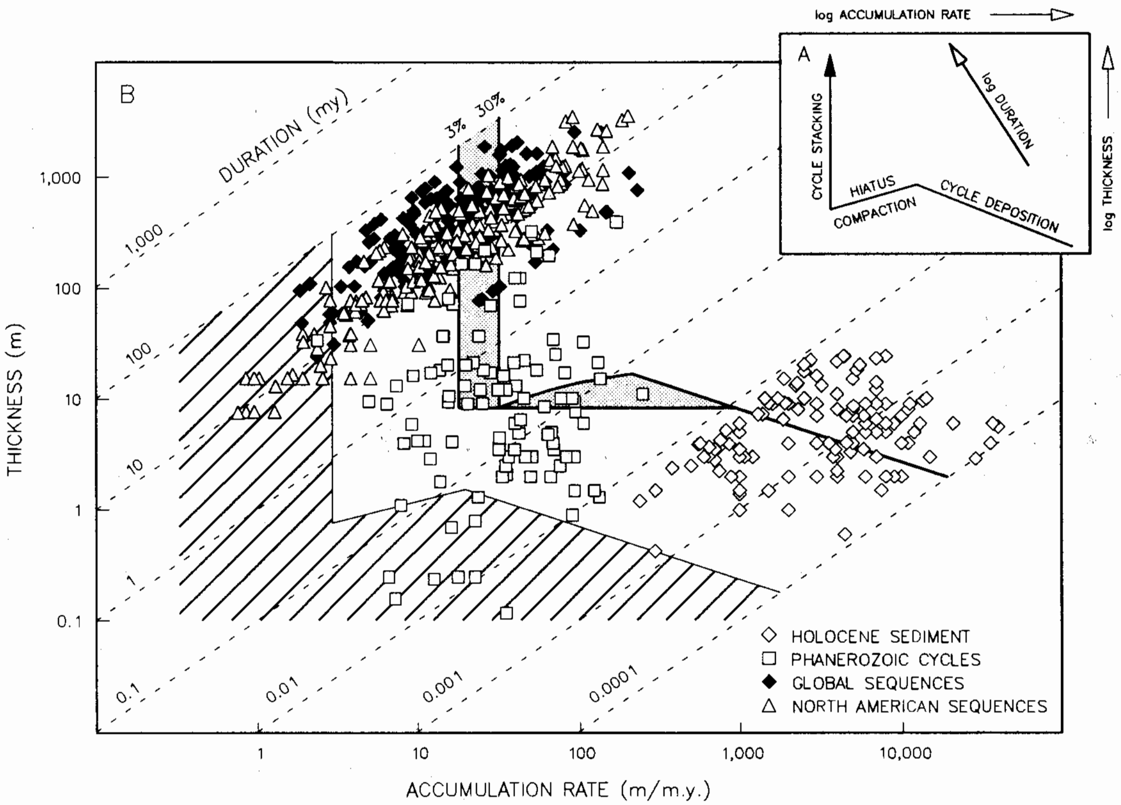

Figure 3. Relations of carbonate-accumulation rate (horizontal axis), thickness (vertical axis), and duration (diagonal lines) among Holocene sediment, Phanerozoic cycles, global sequences, and North American sequences. A: Theoretical (unscaled) path followed during cycle deposition, hiatal compaction, and cycle stacking. B: Bold lines and stippled area delineate range of path trajectories between 3% (0% compaction; net rate = 14.0 m/m.y.) and 30% (50% compaction; net rate = 32.2 m/m.y.) stratigraphic completeness, assuming mean cycle thickness of 8.2 m. Area of diagonal lines to lower left represents thin, low-accumulation-rate Phanerozoic units not represented by Holocene data, because they would require measurement of millimetre-scale accumulation rates in modern settings.

a trend generally independent of the rock types being measured (Fig. 1). Such relations are typical of sedimentary sequences (Sadler, 1981) and reflect the decreasing variation in the ratio of depositional time to hiatal time with the increasing time interval over which accumulation rate is determined.

Data on 98 cyclic open-marine and tidal-flat–capped marine sections were also tabulated from the literature (Algeo and Wilkinson, 1988). The average thickness of each section and contained cycle was divided by long-term sedimentation rate to arrive at long-term accumulation rate and average cycle period (e.g., Grotzinger, 1986). Epoch-interval isopach and lithofacies maps of 247 contiguous North American carbonate sequences were planimetered from Cook and Bally (1975), and thicknesses and rates of accumulation were calculated. Additional long-term data were taken from a series of tabulations by Ronov (1980) that include epoch-interval areas and volumes of 214 platform and geosynclinal carbonate lithofacies associations for Africa, Australia, Eurasia, North America, and South America (Figs. 2 and 3).

DISCUSSION

Several aspects of platform carbonate accumulation are apparent from available data. First, Holocene sediment thicknesses are largely independent of accumulation rate (Figs. 1 and 3); this lack of correlation reflects the incorporation of greater numbers of small intracycle hiatal intervals as duration increases, and lack of a record of small and "negative" accumulation events at shorter durations. Thus, it is not possible to determine a representative value of accumulation rate unless duration is also specified.

Second, Phanerozoic cycle accumulation rates are of the same magnitude as those of North American and global Phanerozoic sequences (Fig. 2). Given that most carbonate is generated and deposited at relatively shallow depths, it follows that net accumulation is controlled by rate of platform subsidence. However, ancient accumulation rates are about two orders of magnitude lower than modern rates (Fig. 3). This difference requires that significantly greater amounts of hiatal time are incorporated into ancient sequences, but only after the passage of depositional durations longer than those of Holocene sediment.

If modern accumulation rates are representative of those in ancient seas, the Holocene equation can be rearranged such that duration (D) of the accumulation of any carbonate cycle (C) is given by:

$$\log D_{(m.y.)} = (\log C_{[m]} - 1.6)/(1 - 0.7).$$

When long-term accumulation rate and net cycle period (P) are also constrained by data on sequence thickness and age, stratigraphic completeness (D/P) for each cycle can be calculated for any estimate of compactional shortening. Holocene duration and accumulation-rate data uniquely constrain that part of cycle period during which any thickness of accumulation occurred, whereas long-term accumulation rate and/or total

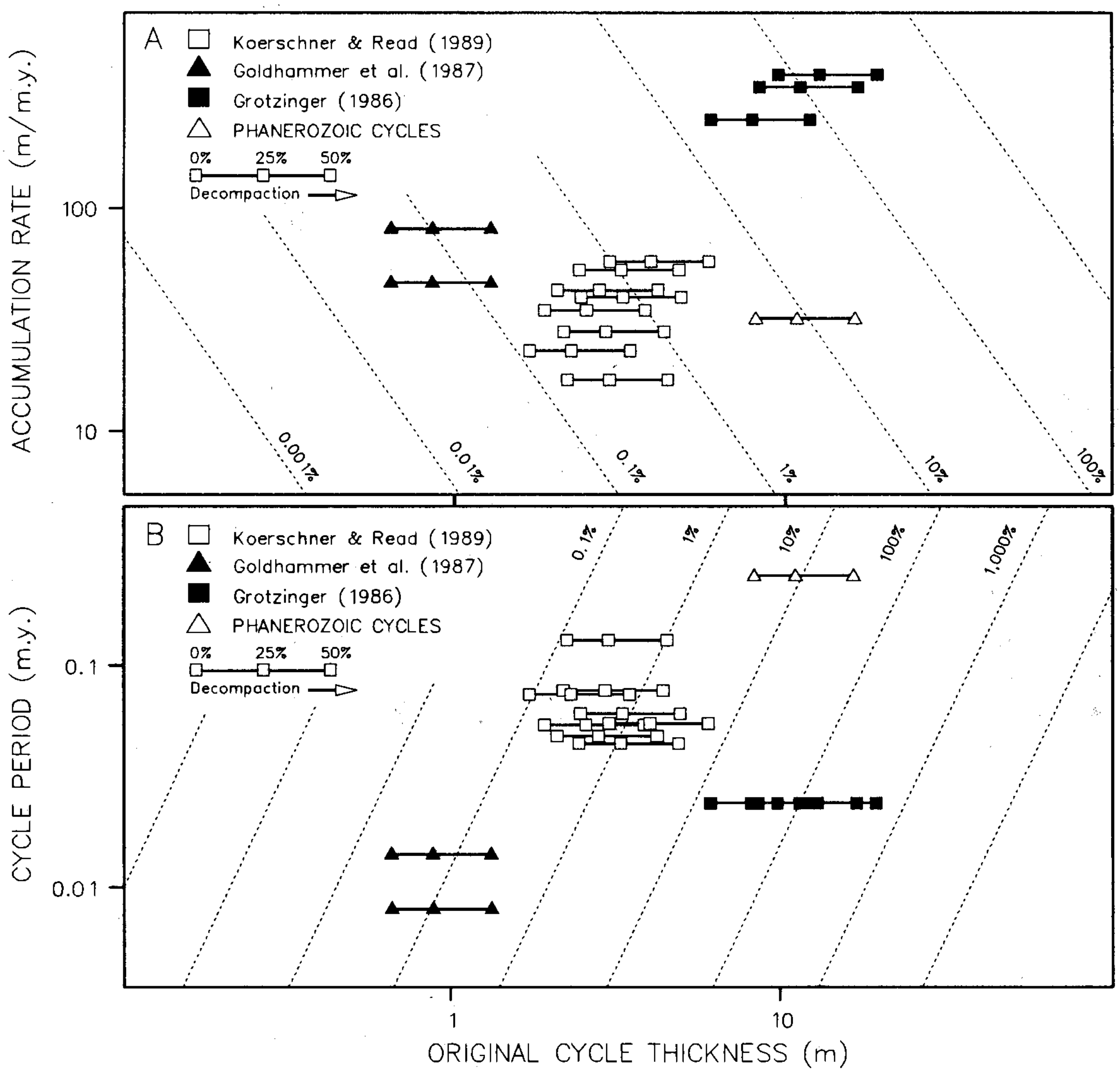

Figure 4. Stratigraphic completeness (diagonal lines) as function of original cycle thickness (horizontal axis) relative to long-term accumulation rate (A) and net cycle period (B). Koerschner and Read (1989) data for cycles in Middle to Upper Cambrian Elbrook and Conococheague Formations in southern Appalachians; data from Goldhammer et al. (1987) for Middle Triassic Latemar buildup in northern Italy; Grotzinger (1986) data for Early Proterozoic Rocknest Formation in northwest Canada. Depending on amount of compactional thinning, stratigraphic completeness among these examples ranges from nearly 100% (Proterozoic cycles) to about 0.1% (Triassic cycles). For comparison, average Phanerozoic cycle completeness ranges from 3% to 30%.

cycle period data yield that part of cycle period represented by hiatal time. Stratigraphic completeness increases with increasing cycle thickness, with higher net accumulation rate, and with greater compactional shortening.

In global cratonic carbonates (Fig. 3) a mean Phanerozoic cycle thickness of 8.2 m (Fig. 2) yields stratigraphic completenesses between 3% (assuming 0% compaction and a net accumulation rate of 14.0 m/m.y.) and 30% (assuming 50% compaction and net accumulation at 32.2 m/m.y.). In individual metre-scale cycles, we have also used cycle thickness and periodicity data for the Middle to Upper Cambrian Elbrook and Conococheague Formations in the southern Appalachians from Koerschner and Read (1989), for the Middle Triassic Latemar buildup in northern Italy from Goldhammer et al. (1987), and for the Early Proterozoic Rocknest Formation in northwest Canada from Grotzinger (1986) in order to determine stratigraphic completeness at these localities. On the basis of these data, and depending on assumptions of compactional shortening, Early Proterozoic Rocknest cycles are nearly complete, whereas Cambrian Elbrook and Conococheague cycles range from about 0.1% to 6.0% complete, and those of the Middle Triassic Latemar buildup represent only 0.02% to 0.36% of net sequence duration (Fig. 4).

The accuracy of such completeness data can be questioned for any particular sequence, in part because the amount of compaction is largely unconstrained, but primarily because Holocene rates from which they were determined vary by a factor of about 40 when normalized to a common duration; in addition, ancient cyclic sequences undoubtedly accumulated under different rates of sediment deposition in different environmental and tectonic settings. Conversely, such completeness values are in agreement with those determined for average cratonic sequences and, at a global scale, strongly suggest that shallow-water carbonate sequences typically incorporate a relatively small fraction of geologic time.

One of the more important consequences stemming from such a small value is that it may serve to distinguish between various now-popular scenarios of cycle generation. At present, some uncertainty exists as to the relative importance of global change in sea level as opposed to localized change in sedimentation rate in the generation of upward-shallowing cratonic carbonate units. The primary difference between global eustatic-based allocyclic models and local accumulation-based autocyclic models relates to perceptions of nondepositional time duration at cycle contacts. End-member allocyclic models usually embrace scenarios of more-or-less continuous deposition during episodic sea-level rise and shelf flooding, whereas autocyclic models generally presuppose invariant sea level and rapid deposition during an even smaller fraction of cycle period. Because accumulation rates are much higher in modern settings than in ancient sequences, one might anticipate that autocyclic models are more probable. However, most simulations (e.g., Koerschner and Read, 1989) argue for allocyclic eustatic control, shallowing-upward deposition during sea-level rise being derived through (1) use of low values of sediment accumulation, (2) assumption of low amplitudes (low rates) of sea-level change, and (3) inclusion of some amount of autocyclic "lag time" between craton flooding and initiation of sediment deposition. Although employment of such assumptions commonly produces simulated sequences that resemble cratonic cycles, model durations of deposition commonly range toward 50% of eustatic period (e.g., Goldhammer et al., 1987).

Time partitioning values derived from Holocene and Phanerozoic sequences suggest that such accumulation durations are much too long, at least in a context of global carbonate deposition. Accumulation relations suggested by modern and ancient sequences should therefore be more closely considered when evaluating the importance of allocyclic eustatic processes in the generation of cyclic cratonic carbonates.

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ACKNOWLEDGMENTS

Research on patterns of carbonate accumulation at the University of Michigan is supported by National Science Foundation Grants EAR-88-03901 and EAR-90-19095. We thank Bob Demicco, Bob Ginsburg, John Grotzinger, and Fred Read for cycle-lore discussions that precipitated this project, and Catherine Badgley, Carl Drummond, Tracey Frank, John Grotzinger, Paul Howell, Henry Mullins, and Thomas Worsley for helpful reviews.

Manuscript received April 8, 1991
Revised manuscript received July 22, 1991
Manuscript accepted July 29, 1991

Reviewer's comment

Results have great bearing on imposing a uniformitarian interpretation upon rates of accumulation of ancient carbonate deposits and strongly suggest that carbonate accumulation is almost always very rapid.

Thomas Worsley