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UPWARD SHALLOWING PLATFORM CYCLES: A RESPONSE TO 2.2 BILLION YEARS OF LOW-AMPLITUDE, HIGH-FREQUENCY (MILANKOVITCH BAND) SEA LEVEL OSCILLATIONS

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Abstract. Shallow-water carbonate platforms, characterized by sequences of small-scale upward shallowing cycles, are common in the Phanerozoic and Proterozoic stratigraphic record. Proterozoic small-scale cycles are commonly 1 to 10 m thick, have asymmetrically arranged facies, and are strikingly similar to Phanerozoic platform cycles. In some platform sequences (eg. Rocknest, Wallace, and Helena formations of early to middle Proterozoic age), it can be demonstrated that the lateral distribution of facies within cycles relates to systematic variations in platform paleogeography and topography. In the Rocknest formation, cycles with intervals of tepees and pisolitic breccia formed on a topographic high (shoal complex) near the shelf edge rim, and provide evidence for eustatic falls in sea level at the end of each cycle. The presence of these facies in other Proterozoic cyclic platforms also suggests that eustatic sea level falls may have been important in the development of each cycle. Proterozoic upward shallowing cycles appear to have had periods of between 20,000 and 100,000 years, and probably formed during eustatic oscillations in sea level with amplitudes of less than 10 m. This suggests that cyclicity may have been regulated by Milankovitch band climatic forcing, perhaps influencing global sea level through minor changes related to small-scale continental or alpine glaciation. It is possible, then, that Milankovitch band climatic forcing has occurred for at least the last 2.2 billion years of earth history.

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INTRODUCTION

The stratigraphic record of geologic history is characterized by intervals of pronounced rhythmic or cyclic arrangement of facies such that repetitive groups of rock units have component facies which tend to occur in certain order. Sedimentary cyclicity has been documented in many paleoenvironmental settings ranging from fluvial to deep sea, in both carbonate- and siliciclastic-dominated systems [e.g. Beerbower, 1964; Hays et al., 1976; Olsen, 1984; Arthur et al., 1984; James, 1984; Goodwin and Anderson, 1985]. Both autogenic and allogenic models have been proposed to account for this cyclicity, but in recent years new evidence has been collected that is compatible with a Milankovitch-forced control over many cyclic systems.

The effect of Milankovitch band forcing on cyclicity of Pleistocene deep sea sediments is almost irrefutable [Hays et al., 1976], and Milankovitch band forcing is probably the cause of cyclicity in earlier Cenozoic [Mathews and Poore, 1980], Cretaceous [Arthur et al., 1984], and Jurassic deep water sequences. The recognition of Milankovitch band climatic forcing in Cenozoic and Mezozoic deep

Fig. 1. Location of Rocknest formation, Wopmay orogen, northwest Canadian Shield.

marine sediments has been successful primarily becase of three factors: (1) other extrinsic controls such as episodic subsidence have a minimal effect on stratigraphic accumulation in the deep-sea environment, (2) the deep-sea record tends to be more complete than that of platform sediments, and (3) biostratigraphic and magnetostratigraphic zonation are excellent for the Cenozoic and Mesozoic. In fact, the evidence is so overwhelming for a Milankovitch-forced climatic control over Cenozoic and Mezozoic deep marine cyclicity that it has been suggested to adopt the use of sedimentary cycles in determining the true length of chronostratigraphical zones as a new approach towards establishing an absolute time scale [House, 1985].

The mechanisms responsible for cyclicity in shallow-water marine platform sediments are less certain [Weller, 1964; Wilkinson, 1982; James, 1984]. Although a Milankovitch band forcing effect has long been suspected [Gilbert, 1895; Weller, 1930; Fischer, 1964], new evidence is being gathered which supports this model [Goodwin and Anderson, 1985; Grotzinger, 1985, 1986b; Read et al., 1986; Heckel, 1986]. However, general acceptance of the Milankovitch model for shallow-water sediments has been slow because of a lack of understanding of the local mechanisms which govern platform cyclicity, and how, if important, a Milankovitch control would regulate platform cyclicity. These problems arise primarily from poor exposures of many cyclic platforms, which prohibits detailed studies of individual cycles on a lateral basis, in turn leading to a poor understanding of cycle dynamics and determinant mechanisms.

This paper provides new insights into the general question of cyclicity of shallow-water platforms in geologic history by (1) discussing the paleogeography and cycle dynamics of a superbly exposed early Proterozoic cyclic platform and its significance in understanding general mechanisms of cyclicity, (2) discussing general models for the development of platform cycles, independent of age, and (3) reviewing the occurrence and possible causes of other cyclic sequences in the Proterozoic record, thereby establishing that cyclic platform sedimentation, and perhaps Milankovitch band forcing, has been important for at least the last 2.2 billion years of earth history.

MECHANISMS OF CYCLICITY, ROCKNEST PLATFORM

The early Proterozoic (1.9 Ga) Rocknest formation is exposed in Wopmay orogen, northwest Canada (Figure 1). It is part of a continental margin sedimentary prism composed of a basal rift sequence, a middle passive-margin sequence, and overlying foredeep sequence [Hoffman, 1980; Hoffman and Bowring, 1984]. The upper part of the passive-margin sequence (Rocknest formation) is a cyclic, dolomite shelf sequence with a stromatolitic reefal rim and flanking debris apron [Grotzinger, 1985, 1986a, b].

The palinspastically restored shelf sequence (Figure 2) is an eastward thinning prism, up to 1 km thick, extending for over 220 km parallel to depositional strike and over 200 km perpendicular to strike [Grotzinger, 1985, 1986a, b). The shelf sequence can be divided from west to east into slope, outer shelf, shoal complex, and inner shelf facies (Figure 3). Slope, outer shelf and shoal complex facies assemblages are restricted to the western margin of the shelf; inner shelf facies occur over most of the shelf region except adjacent to its margin. Slope and outer shelf facies are discussed in detail by Grotzinger [1985, 1986a], and are not reviewed further here. Shoal complex and inner shelf facies are briefly reviewed here as they pertain to shelf cyclicity, and more detailed discussions of these facies can be found in reports by Grotzinger [1985, 1986b].

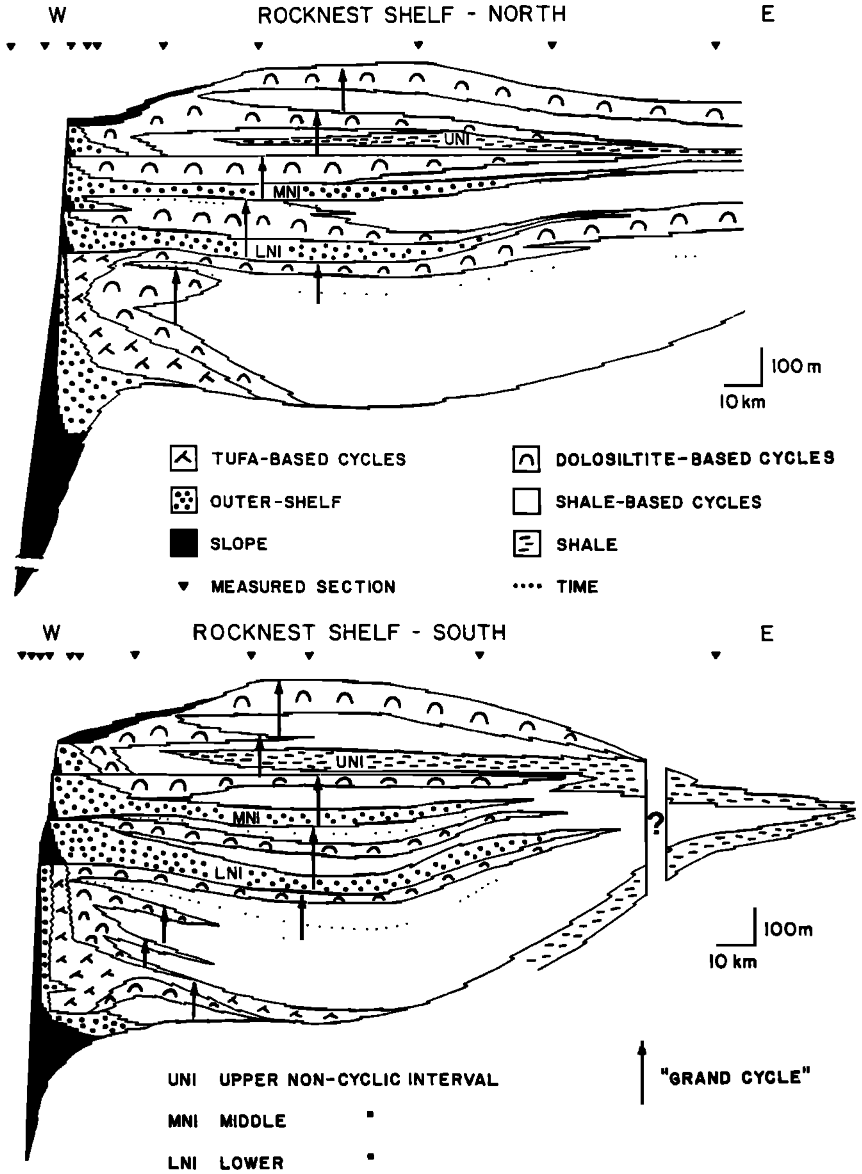

Fig. 2. Palinspastic cross sections of Rocknest shelf stratigraphy. Note well developed W-E facies zonation including slope, outer shelf (rim boundstone and backreef grainstone), shoal complex (tufa-based cycles), proximal inner shelf (dolosiltite-based cycles), distal inner shelf (shale-based cycles), and lagoon (shale).

<u>Shoal Complex</u>

Lithofacies. Shoal complex facies occur in a narrow belt, 1 to 5 km wide (Figures 2 and 3). Sediments are arranged cyclically, so that cryptalgalaminite, tufa, and laminated dolosiltite and lutite are overlain by disrupted equivalents, developed as tepees and breccias with associated pisolite (Figure 4).

During the course of cycle development at the shoal complex, deposition of laminated dolosiltite and lutite, cryptalgalaminite, and tufa was followed by lowering of the water table and establishment of a vadose zone which favored tepee,breccia and pisolite formation. These facies are critical in deriving the mechanism responsible for cyclicity, suggesting strongly that

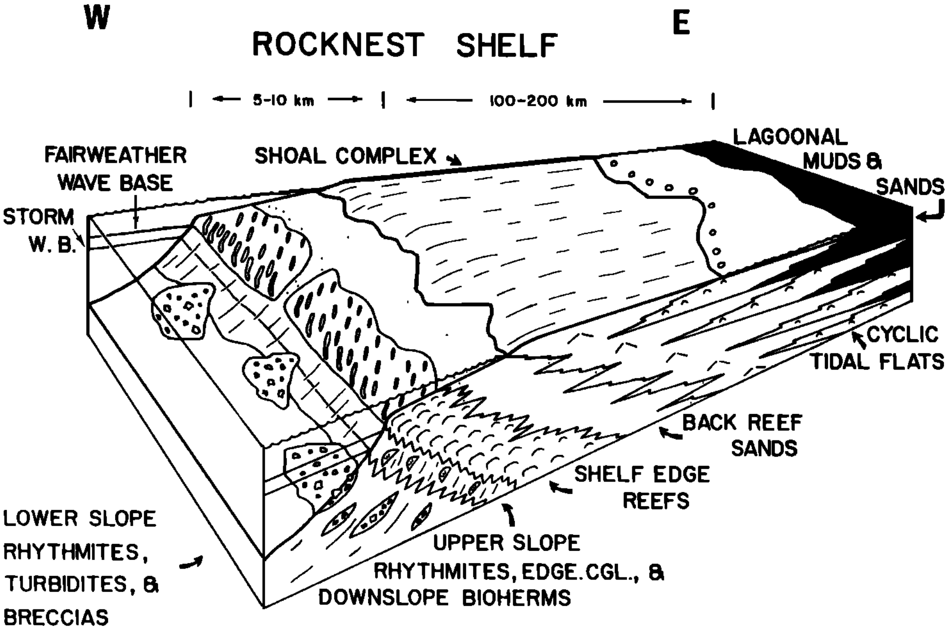

Fig. 3. Rocknest shelf paleogeography. Cyclic deposits formed by limited westward and extensive eastward progradation of shoal complex in response to low-amplitude, high-frequency sea level oscillations (see text).

eustatic sea level falls were important in establishing a vadose zone at the top of each cycle.

Interpretation. Cyclical sequences in the shoal complex are interpreted to reflect low-amplitude, high-frequency oscillations in sea level [Grotzinger, 1985, 1986b]. Initially, upper intertidal to supratidal sedimentation occurred during small rises in sea level and shallow flooding of the shoal complex by the inner shelf lagoon. Subtidal water depths were not achieved because of the positive topography of the shoal complex. During subsequent falls in sea level the eastern margin of the shoal complex prograded away from the rim (up to 200 km), forming upper intertidal to supratidal caps of inner shelf cycles; as sea level fell below the sediment surface, earlier formed sediments of the western shoal complex were exposed in the vadose zone, and tepees, breccias, and pisoliths developed as soils. Depth and intensity of vadose zone development reflects position on the shoal complex. Following subaerial exposure and soil development, submergence of the shoal complex during the next cyclical transgression reinitiated upper intertidal to supratidal sedimentation.

Inner Shelf

Lithofacies. Inner shelf facies occur over a broad belt (several hundred kilometers) and pass westward into shoal complex facies and eastward into lagoonal siliciclastic shale, siltstone, and sandstone. Generally, inner shelf facies occur in asymmetric, upward shallowing cycles which can be classified according to cycle base lithology, reflecting paleogeographic position on the shelf (Figure 4). Shale-based cycles have the most diverse facies and contain, from base to top, (1) intraclast packstone, (2) siliciclastic siltstone and sandstone and argillaceous dololutite, (3) thick-laminated dolosiltite, (4) stromatolitic-thrombolitic dolomite, (5) crypt-algalaminite, and (6) laminated to microdigitate tufa.

Interpretation. Shale-based cycles formed on the inner shelf when tidal flats were submerged following maximum transgression. The upward increase in carbonate beds within shale-based cycles reflects diachronous progradation of the carbonate tidal flats, from west to east, over deeper siliciclastic-rich lagoonal sediments. Thick-laminated dolosiltites accumulated close to fair weather wave base and have abundant wave ripples and edgewise conglomerates. Stromatolitic-thrombolitic dolomite formed when the sediments shoaled into the upper subtidal and intertidal zones, and crypt-algalaminites and tufas formed in the upper intertidal to supratidal zones.

Asymmetric cycles of the inner shelf probably formed by rapid submergence of

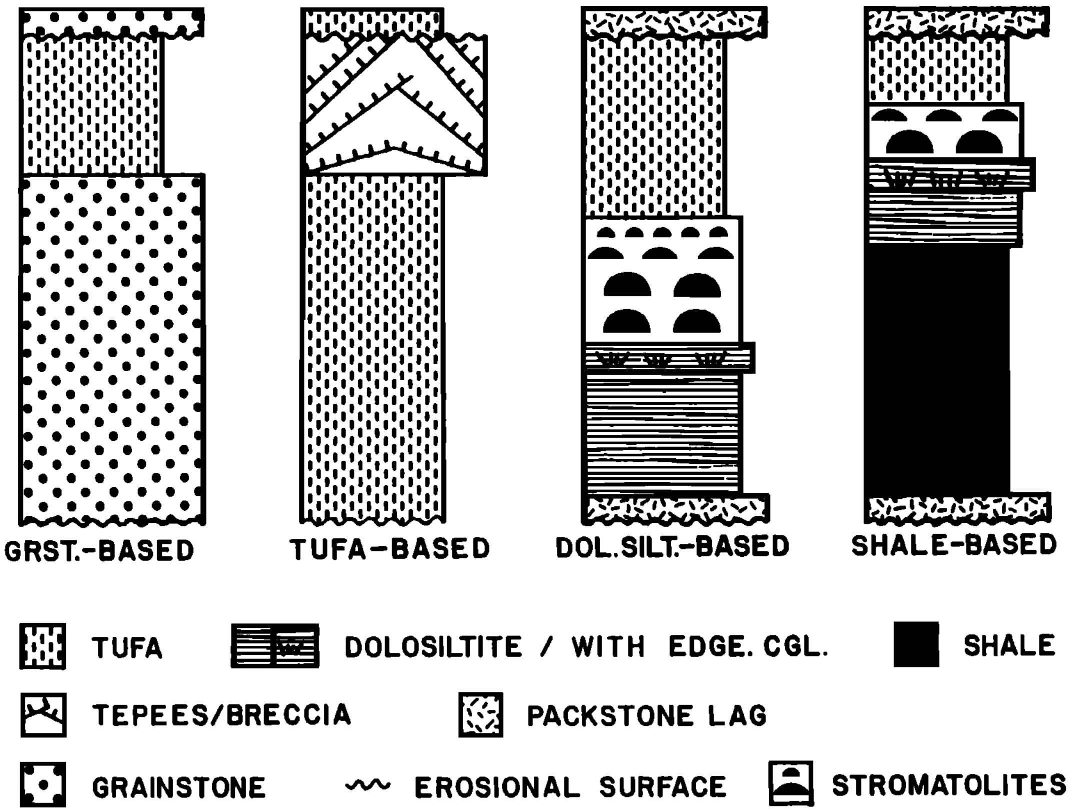

Fig. 4. Rocknest cycle types. Cycle types are a function of paleogeographic position on the platform and primarily reflect platform slope; tufa-based cycles formed on the topographically high shoal complex, and shale-based cycles formed on the topographically low inner shelf (compare with Figure 3).

the inner shelf followed by gradual shoaling to sea level (Figure 5). Cycles were intiated by rapid transgression and flooding of carbonate tidal flats flanking the eastern margin of the shoal complex (Figure 5a), followed by eastward expansion of the shoal complex and progradation of tidal flats over "lagoonal" facies of the inner shelf (Figure 5b). At the end of each progradation event, the shoal complex had a maximum width of over 200 km, which shrank following each transgression to a minimum width of 1 to 5 km [Grotzinger, 1985, 1986b].

Rocknest Cycle Dynamics

Quantification of cycle period, amplitude of sea level oscillation, slope of the inner shelf at high and low sea level stands, and progradation rates of tidal flats is important in clarification of the mechanism(s) responsible for cyclic sedimentation. The methods and procedures involved in these calculations, which can be done for cyclic platforms of any age, are presented in Grotzinger [1985, 1986b].

Period. The average cycle period is obtained given duration of the passive-margin sequence in which the Rocknest formation occurs, the duration of the Rocknest Formation, and the total number of cycles it contains [Grotzinger, 1985, 1986b]. The calculated range of average cycle period, including all errors except those associated with geochronological interpretation, is 18,000 to 30,000 years/cycle. Given that geochronological estimates of the duration of the passive-margin sequence could be too low by as much as a factor of 3, this would increase the range of average cycle period to 18,000 to 90,000 years/cycle. Although these values span a large range, the fact that these are 10^4-year cycle periods is important and provides evidence in favor of cyclic oscillations in sea level within the Milankovitch frequency band. For the calculation of sea level oscillation amplitude [Grotzinger, 1985, 1986b], it was assumed that the range of average cycle period was 18,000 to 30,000 years, using the geochronological estimates provided by Hoffman and Bowring [1984].

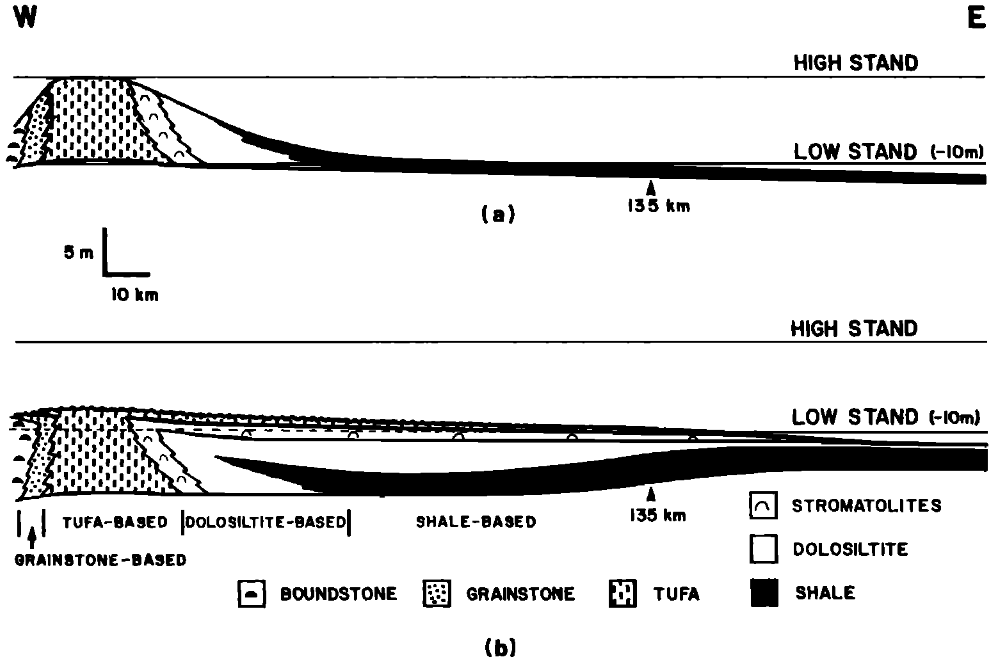

Fig. 5. Profiles of Rocknest platform at high and low stands of sea level. (a) Slope of platform at high sea level stand based on documentation of lateral facies transtions within individual cycles. Note that shoal complex sedimentation occurs primarily during sea- evel rise and that only a thin veneer of sediment is deposited over most of the inner shelf. (b) Platform slope and facies relations within a single cycle at low sea level stand. Note that inner shelf sedimentation occurs primarily during sea level fall.

For convenience and simplicity in the following sections, an averaged value of 24,000 years is used for period.

Amplitude. In cyclic sequences that form by eustatic changes in sea level, erosional caps bounding cycles are produced only if the rate of sea level fall exceeds subsidence rate, in which case sea level will eventually drop below the surface of the platform, exposing it to subaerial weathering and vadose diagenesis [Grotzinger, 1986b]. For the Rocknest platform, minimum sea level oscillation amplitudes must be greater than 7 to 9 m to get sea level fall rates that are faster than subsidence rates. This will result in subaerial exposure of the platform and production of erosional capped cycles.

Estimating the maximum amplitude of sea level oscillation is possible for the lower part of the Rocknest formation where the shoal complex was permanently aggraded. Because the shoal complex was never submerged below the upper intertidal zone during each cyclic transgression, it follows that sedimentation kept pace with sea level rise to its maximum height during each oscillation. Thus the average maximum amplitude of sea level oscillation could not have been greater than the average thickness of shoal complex cycles which record amplitude, minus subsidence that occurred during each cyclic sea level rise. This procedure yields an average maximum amplitude of approximately 10 m [Grotzinger, 1985, 1986b].

Forward Modeling of Rocknest Cycles

Quantification of parameters such as period and amplitude of sea level oscillation, inner shelf slopes, and tidal flat progradation rates is essential to understanding the distribution of facies, both horizontally and laterally, within cycles of any age. Qualitative distillation of a cyclic sequence to generate an "ideal cycle" should be avoided, as this creates a false understanding of the critical transitions between cycles and individual facies within cycles and ultimately prohibits extraction of the true mechanisms governing cyclicity. In the case of the Rocknest platform, several different cycle types are recognized, both on a lateral basis as a function of predictable changes in platform paleogeography and topography (Figures 3 and 5) and on a vertical basis as a function of systematic, longer-term changes in sea level oscillation amplitude and period, subsidence rate, and sedimentation rates [Grotzinger, 1985, 1986b].

Given a set of independent variables that control cyclicity, forward modeling can be used to quantify the effect of each variable on the cyclic system [Read et al., 1986]. The modeling leads to a greatly enhanced understanding of facies development within cycles. The model variables are period, amplitude and symmetry of sea level oscillation, depth-dependent sedimentation rate, lag time in carbonate production following submergence, tidal range, and linear subsidence (Figure 6a). All variables are independent of each other, but for the Rocknest platform several variables can be fixed, permitting approximation of values for the others.

Shale-based cycles formed on the distal inner shelf by submergence of the platform during sea level rise followed by eastward progradation of the shoal complex over deeper subtidal mixed carbonate-siliciclastic facies during sea level fall. Forward modeling constrains lag time and sedimentation rates if other variables (e.g. period and amplitude of sea level oscillation) are fixed independently. For the distal inner shelf the subsidence rate was approximately 25 cm/1000 years [Grotzinger, 1985, 1986b]. Modeling of a shale-based cycle at the point on the platform where tidal flat caps pinch out (135 km east of the western shoal complex), shows that lag time must be at least 2000 years in order to get submergence to depths where mixed carbonate-siliciclastic (deeper subtidal) sedimentation occurs (Figure 6b). Given a 2000 year lag time, modeling shows that the rate of deeper subtidal sedimentation must be close to 20 cm/1000 years. Rates faster than this would cause shallowing to sea level before the end of the cycle and would generate thick tidal flat facies. Furthermore, premature shallowing would allow time for exposure of the platform during the final stages of sea-level fall. Neither thick tidal flat facies or vadose features are seen where tidal flat caps pinch out. Deeper subtidal sedimentation rates much slower than 20 cm/1000 years would cause incipient drowning of the platform. Thus shale-based cycles that form where tidal flat caps pinch out have thin to absent tidal flat units and are separated by conformable cycle boundaries. Forward modeling provides quantitative solutions to questions generated by field investigations that would be difficult to obtain otherwise.

Forward modeling of other cycle types (tufa based and dolosiltite based) in the Rocknest formation has also yielded significant information on sedimentation rates, lag times, and thickness of vadose profiles across the platform. Most importantly, the modeling demonstrates that it is possible to synthetically generate many types of platform cycles using high- frequency, low-amplitude sea level oscillations within the Milankovitch band. The distribution of facies within cycles and the degree of disconformity between cycles is determined to be a direct result of the superimposition of oscillatory sea level on the variable topography associated with a well developed paleogeographic zonation.

DEVELOPMENT OF UPWARD SHALLOWING CYCLES IN THE GEOLOGIC RECORD: A DISCUSSION OF MECHANISMS

Autocyclic Mechanism

Upward shallowing cycles in platform sequences can be produced by autocyclic or allocyclic mechanisms [Beerbower, 1964; Fischer, 1964; Ginsburg, 1971; Wilkinson, 1982; James, 1984; Mathews, 1984]. Cyclicity within the autocyclic model is essentially intrinsic, involving feedback interactions between different parts of the system. Several variations on the autocyclic mechanism as it applies to carbonate platforms have been proposed [Ginsburg, 1971; Wilkinson, 1982; James, 1984], but all are ultimately controlled by the rate of carbonate production as a function of source area size. Sedimentation takes place on a stable shelf of fixed width subsiding at differential but constant rates and under stationary or slowly rising sea-level. Carbonate sediments are produced in an initially large subtidal area and transported landward [Ginsburg, 1971], resulting in tidal flat progradation. During progradation the subtidal source area (or "carbonate factory") is gradually reduced in size until it fails to provide sufficient sediment to the prograding wedge, and sedimentation and progradation are arrested. Subsequently, background differential subsidence of the platform combined with stalled sedimentation results in relative sea level rise over the platform until water depths are once again deep enough to efficiently generate sediment. This starts the next cycle of progradation. As such, rapid shoaling occurs during progradation, and slow deepening occurs during nondepositional

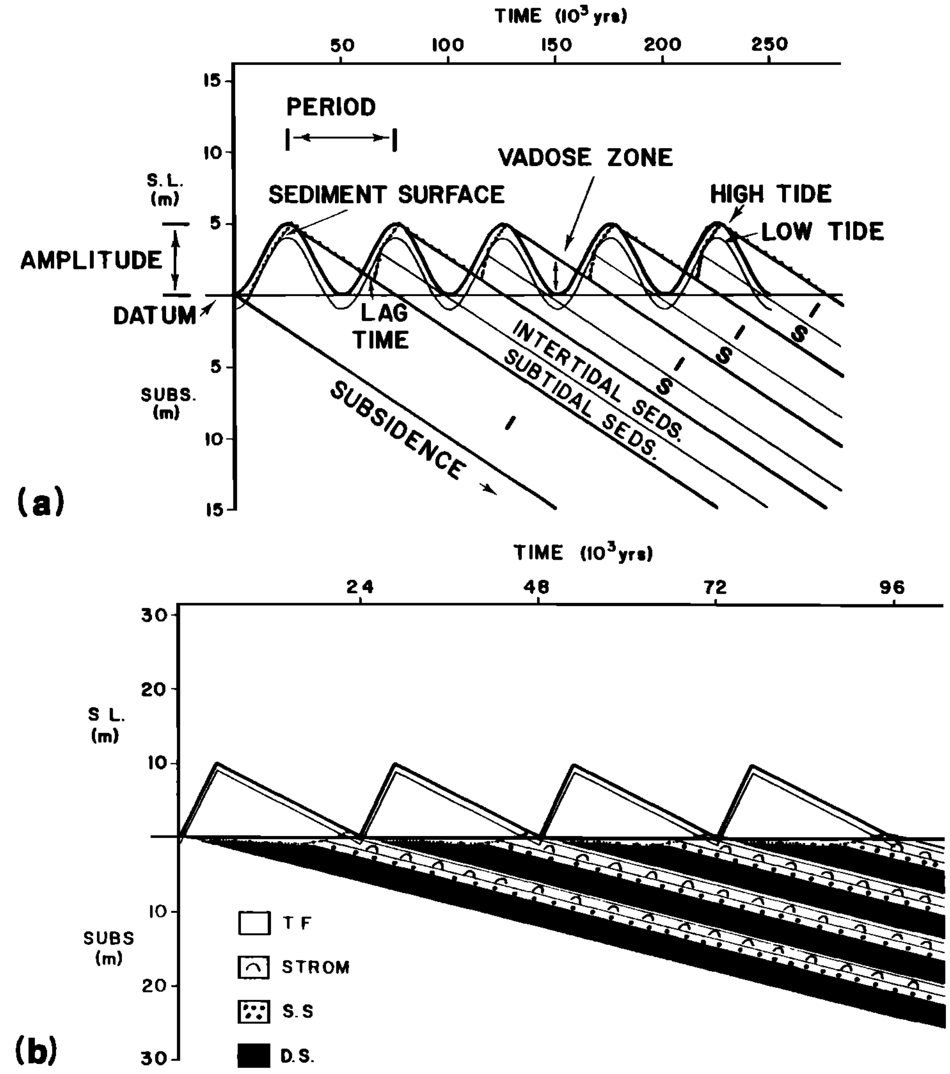

Fig. 6. Forward model of Rocknest cycles: general model and inner shelf model. (a) General model with arbitrary values: period, 50,000 years; amplitude, 5 m; symmetrical sea level oscillation function; lag time, 5000 years; subsidence rate, 10 cm/1000 years; tide range, 1 m; subtidal sedimentation rate, 100 cm/1000 years; intertidal sedimentation rate, 50 cm/1000 years. With time, sea level rises according to sine function, and the sediment surface subsides because of lag time. After 5000 years, water depths are near the low tide zone, and sedimentation begins (the dotted line marks aggrading sediment surface). Sea level then peaks and starts to fall, but sedimentation continues to high tide, intercepting sea level shortly after its high stand. As sea level falls, the platform is exposed because the rate of sea level fall is greater than subsidence rate, and a vadose zone is formed. Subsequent cycles have well-developed subtidal bases because the subsiding platform is not submerged until about one third of each sea level rise occurs. (b) Forward model of Rocknest inner shelf cycles. Variables are as follows: period, 24,000 years; amplitude, 10 m; 20% of cycle period in sea level rise; lag time, 2000 years; subsidence rate, 25,000 cm/1000 years; deep subtidal (shale) sedimentation rate, 20 cm/1000 years; shallow subtidal (dolosiltite) sedimentation rate, 80 cm/1000 years; stromatolite sedimentation rate, 100 cm/1000 years; tidal flat (tufa) sedimentation rate, 50 cm/1000 years. All variables are fixed independently using field data, except lag time and sedimentation rates. A lag time of at least 2000 years is required to produce initial submergence to deep subtidal depths before sedimentation begins. Following the expiration of lag time, a deep subtidal sedimentation rate of 20 cm/1000 years for shale facies prevents rapid upbuilding of the platform so that it will not be significantly exposed at low stand.

submarine hiatus. Autocycles should only be affected by minor vadose diagenesis, related to shallow depression of the water table by evaporative drawdown [cf. Read, 1973].

The autocyclic model is popular because it does not require "sudden" eustatic changes in sea level or subsidence. However, some consequences of the autocyclic model are as follows: (1) progradation can only occur if there is differential subsidence across the platform, (2) progradation must proceed in the direction of increasing subsidence, (3) cycles must always shoal to sea level, and (4) cycles should not be significantly affected by vadose diagenesis. Therefore cycles should be wedge shaped and show evidence of progradation in the direction of increasing subsidence [cf. Wilkinson, 1982, Figure 5); contrary evidence would support an allocyclic model. Although some cyclic sequences have been shown to prograde in the direction of increasing subsidence [e.g. Lohmann, 1976], others clearly prograde in the direction of decreasing subsidence [Aitken, 1978; Koerschner, 1983; Grotzinger, 1985, 1986b]. The latter can only be explained by an allocyclic model.

Furthermore, the allocyclic model has a fundamental weakness in that it fails to explain the transition from prograded platform to submerged platform (i.e., the cause of transgression). If the progradation rate is controlled only by the rate of sedimentation (implicit in autocyclicity), then certainly it must be highest when the subtidal source is largest, decreasing with time as the area of the "factory" is reduced. In this system the direct feedback relationship between sediment supply and progradation requires that the system approach a state of dynamic equilibrium; the prograding wedge will reach a point where the limit of production is such that the tidal flats will remain more or less stationary and track subsidence.

Also, even if sedimentation was arrested so that transgression could occur, it is unlikely that deepening could occur because subsidence rates on cratons (1 to 5 cm/1000 years) and mature passive margins (5 to 10 cm/1000 years) where most cyclic carbonates form, are too slow to generate sufficient water depths within a reasonable amount of time. For example, at 5 cm/1000 years, it would take 20,000 years to generate 1 m of water depth. Generating water depths of several meters (typical of subtidal facies of cycles) is difficult with an autocyclic model.

Finally, the autocyclic model cannot explain incomplete shallowing to sea level. Autocycles must shoal to sea level in order for carbonate production and progradation to be arrested. Theoretically, progradation should continue to a limit where carbonate production is decreased because of several possible effects (e.g., water too shallow; water too deep; siliciclastic influx too high). Because many cycles of different sequences show arrested progradation [Grotzinger, 1985, 1986b] or aggradation [Goodwin and Anderson, 1985] before having reached their potential limit, factors other than shallowing to sea level must be involved in ultimately causing submergence events.

Allocyclic Mechanisms

Cyclicity within the allocyclic model has an extrinsic control, where sedimentary cyclicity is controlled by the forcing effect of an external cyclic or rhythmic system. Fundamentally, the allocyclic model invokes changes in relative sea level caused by episodic subsidence or eustatic sea level events. Consequently, an external control on submergence events can result in premature arrest of prograding tidal flats and incomplete shallowing of the platform to sea level. As in the autocyclic model, progradation occurs in response to deposition of sediment on tidal flats, derived from a subtidal source area. Eustatic sea level may remain stable if cyclicity is related to periodic subsidence or falls if eustatically controlled.

Episodic subsidence model. In the episodic subsidence model, progradation is arrested by sudden submergence of the platform during rapid, incremental subsidence events. Transgression occurs, initiating a new cycle, followed by progradation and shallowing to sea level. This model may be tenable for rift basins where intermittant downfaulting results from relief of tensional stress during extension of the crust. Similarly, it may apply to foredeeps which subside in response to episodic loading of the lithosphere by thrust sheets. Cyclic sequences are known from rift [e.g., Jackson and Ianelli, 1981; Aigner, 1984] and foredeep [e.g., Read, 1980] settings. However, it is unlikely that such episodic subsidence of 10^4 years is important in passive-margin settings or occurs at all in craton interiors, where most cyclic sequences are developed.

Glacioeustatic model. Glacioeustatic-driven change in sea level is the most powerful mechanism for generating cyclic sequences similar to those seen in the

Rocknest formation and elsewhere [e.g., Fischer, 1964; Matthews, 1984; Goodwin and Anderson, 1985; Grotzinger, 1985, 1986b; R. Goldhammer et al., personal communication]. Everything considered, the glacioeustatic model is the best tailored for generating small-scale carbonate cycles. First, oscillations in sea level are asymmetric, favoring relatively slow sea level fall and progradation followed by relatively rapid transgressions. Second, transgressions are fast enough to effectively terminate carbonate production and cause submergence. Third, sea level fall below the platform surface explains the development of vadose profiles ranging from incipient gravels to thick tepee-pisolite sequences. Fourth, a glacioeustatic control can explain why many cycles do not shallow completely to sea level in that the period of sea level oscillation dictates how far tidal flats may prograde between submergence events. Fifth, glacioeustacy is forced by perturbations of the earth's orbit on the scale of 20,000 to 100,000 years, a periodicity recorded in several cyclic sequences ranging in age from early Proterozoic through Triassic. They are 18-30,000 years/cycle [Grotzinger, 1985, 1986b]; 50,000 years/cycle [Fischer, 1964]; 60,000 years/cycle [Koerschner, 1983]; 80,000 years/cycle [Goodwin and Anderson, 1985]; and 100,000 years/cycle [Bova, 1982]. Because these cyclic sequences lack features of major vadose diagenesis it seems likely that most sea level oscillations were small (<10 m), suggesting that either alpine or very limited continental glaciation may have been responsible.

Amplitude of Eustatic Oscillations

Although the range in period of upward shallowing cycles in several sequences is suggestive of astronomic orbital forcing of glacioeustatic oscillations in sea level, the apparent range of oscillation amplitude is not. Most small-scale upward shallowing cycles probably developed in response to sea level oscillations with less than 10-m amplitude [Grotzinger, 1985, 1986b; Read et al., 1986]. Here the Neogene is not applicable in that it was dominated by large-scale fluctuations in amplitude (50 to 100 m), which produced drowning of platforms (rather than shallow submergence) followed by subaerial exposure; "cycles" consist of disconformity-bounded units with intense vadose diagenesis on the inner shelf or pelagic facies capped by thin oolite layers or shallow-water muds on the outer shelf (e.g., late Pleistocene Campeche platform [Logan et al., 1969]). Given the very low slopes of most platforms (5 to 25 cm/km), the rates of eustatic sea level fall could produce shoreline regression rates of 65 km/1000 years. Regression would outpace any attempt by the subtidal carbonate source area to supply sediments to tidal flats, resulting in stranding of tidal flats near high sea level stand if they were ever produced at all. Consequently, an explanation for the production of lower-amplitude glacioeustatic cycles must be sought.

The present distribution of the continents is favorable for production of large ice sheets [Berger, 1980]. Latitudes greater than 60° N are particularly sensitive to climatic changes produced by perturbations in precession of the earth's axis [Imbrie and Imbrie, 1980]. As there are presently large areas of continental mass at latitudes above 60° N, this has led to major glaciations in the late Pleistocene and Holocene. Any change in distribution of landmass (or oceanic currents, by implication) can effect the extent of glaciation and consequently the range of sea level oscillation amplitude [Peltier and Hyde, 1984; Berger, 1980]. By reducing the amount of land north of this climatically sensitive latitude or altering oceanic currents, the magnitude of sea level oscillations will be proportionally decreased. For example, during the early Cenozoic, when it is likely that Antarctica was the only site of major glaciation, deep-sea core data record sea level oscillations with periodicities between 20,000 and 100,000 years, but amplitude is reduced by 30 to 50 m compared with the late Pleistocene [Major and Mathews, 1983; Mathews and Poore, 1980].

Accepting continental drift for the Phanerozoic through late Archean [Hoffman, 1980] and that continental glaciation has occurred intermittently since at least 2.2 Ga (Gowganda tillite [Mial, 1983]), which spans the range of known cyclic carbonates, it is reasonable to assume that there have been times when small-scale glacioeustatic oscillations in sealevel occurred in response to limited continental glaciation. However, given the area of earth poleward of 60°, it seems likely that on average, the continents were not in a favorable position for glaciation. Eustacy in response to development of continental ice sheets of any proportion should have been an exception. However, glaciation may have been important in that mountain belts are sites of limited glaciation and are very sensitive to climatic changes [Fairbridge, 1976]. Thus they have probably had some effect on sea level throughout much of earth history, and because they can store only small amounts of ice, sea level fluctuations have probably been small. Because small-scale carbonate cycles probably formed in response to low-amplitude changes in sea level, it is likely that they may have been produced by alpine glaciation as well as limited continental glaciation.

Period of Glacioeustatic Oscillations

Certain latitudes are more sensitive to insolation changes produced by the different astronomic forcing periods [Berger, 1980]. Therefore the period of glacioeustatic oscillation is dependent on the location of continents and mountain belts with respect to latitude. Consequently, cycle periods will differ in length through time as a function of continental drift. Also, the period of sea level oscillation depends on response time of the lithosphere to ice loading. In turn, response time is sensitive to mantle viscosity [Peltier, 1984]. This suggests that in the Precambrian, when a hotter earth probably had a less viscous mantle, faster isostatic adjustment of ice loads and shorter cycle periods may have occurred.

There also may be a long-term secular trend in the period of precession, obliquity, and eccentricity orbital parameters, which may effect the distribution of average cycle period through time. Because these effects result from gravitational interactions between the earth, moon, sun, and other planets [Berger, 1980], it may be possible that these relationships have evolved through time, similar to the decay in earth spin.

In any cyclic sequence the fundamental range in thickness (i.e., 1 to 10 m, rather than 0.1 to 1 or 10 to 100) is a direct function of platform subsidence rates and cycle period. The order of magnitude range of common cycle thickness (1 to 10 m) is a testimony that most cycle periods ranged between 20,000 and 100,000 years, given that most cyclic platforms probably subsided at rates of 5 to 10 cm/1000 years. The variability in range of fundamental thickness is the interference which results from interaction of cycle period and locally variable subsidence rate. To be sure, the range in thickness is also effected by "noise" within the climatic system (one glaciation not being as extensive as the next, etc.), interference due to migration of the geoid, and longer-term variations in sea level.

If correct, these relationships predict that it should be possible to separate the "noise" from the signal of period, if period is truly important in regulating cycle thickness, as it should be if cycles are controlled by a Milankovitch forcing effect. It should be possible to accomplish this using Fourier analysis, and Olsen [1984] generated a distinct spectral band with peaks corresponding to the Milankovitch frequencies for shallow-water lacustrine deposits of Triassic age. Furthermore, current studies of marine Triassic platform cycles using Fourier analysis have identified 20,000- and 100,000-year sea level oscillation periods (R. Goldhammer et al., personal communication, 1986).

OTHER EVIDENCE OF PROTEROZOIC PLATFORM CYCLICITY

This section briefly reviews the occurrence of other cyclic platforms in the Proterozoic record and their relevance to possible Milankovitch band cyclicity.

Several cyclic sequences occur in the Belt supergroup of the northwest United States. In particular, the Wallace and Helena formations (1.5 to 1.2 Ga) contain thick succesions of cyclic platform sediments [O'Conner, 1967; Eby, 1977; Grotzinger, 1986c]. The Wallace and Helena formations contain over 200 asymmetric siliciclastic-to-dolomite cycles. Cycles are separated by well-defined erosional surfaces and are classified according to cycle base lithology, which reflects paleogeographic location. Cyclic lithofacies include basal intraclastic packstone lags, various types of argillite and sheet sands, and bedded dolomites. These are arranged in repetitive, asymmetric upward shallowing cycles that probably reflect high-frequency oscillations in sea level [Grotzinger, 1986c].

Other cyclic sequences of Proterozoic age include the 2.2 Ga Denault formation [Donaldson, 1963] and Abner formation, the 2.0 Ga Duck Creek dolomite [Grey and Thorne, 1985], the 1.9 Ga Kimerot platform [Grotzinger and Gall, 1986], the 1.7 Ga McCleary formation [Ricketts and Donaldson, 1981], the 1.7 Ga Amelia dolomite [Jackson, 1982], the 1.3 Ga Kendall River formation [Kerans, 1982], the 1.2 Ga Bylot supergroup [Jackson and Iannelli, 1981], and the 0.6 Ga Sarnyere formation [Bertrand-Sarfati and Moussine-Pouchkine, 1983]. All of these sequences are characterized by upward shallowing cycles, on the scale of 1 to 10 m thick.

Facies are asymmetrically arranged and consist of subtidal units of wavy-bedded mudstone, cross-bedded grainstone or stromatolitic bioherms, which grade up into various types of domal-stromatolite sheets, capped by cryptalgalaminites or tufas. In all cases, cycle boundaries are sharp or erosional and are usually brecciated to varying degrees. In some cases, tidal flat facies are extensively disrupted by tepees and thick breccias, supporting the argument that these platforms were subaerially exposed during low stands of high-frequency sea level oscillations.

DISCUSSION

The development of upward shallowing cycles has been an important part of the evolution of shallow-water platforms throughout the Phanerozoic and for most of Proterozoic time and therefore at least the last 2.2 billion years of earth history. There is much evidence, including the asymmetric arrangement of facies and subaerial exposure surfaces, that suggests these cycles formed in response to high- frequency oscillations in sea level. Because the order of magnitude range of cycle thickness (1 to 10 m) has remained constant over this period of time, it seems likely that the average period of cyclicity has remained constant, provided that there has been no offsetting long-term secular change in average platform subsidence rate. The average period of cyclicity is very likely within the Milankovitch band of 20,000 to 100,000 years. Where geochronological constraints permit calculation of average cycle period, this has been shown to be true for the early Proterozoic [Grotzinger, 1985, 1986b]. Such is the case for the Phanerozoic [Fischer, 1964; Koerschner, 1983; Mathews, 1984; Goodwin and Anderson, 1985; Heckel, 1986; R. Goldhammer et al., personal communication, 1986].

Although these studies reveal that the average cycle period of many sequences occurs within the Milankovitch band, this relationship is not conclusive evidence that sedimentary cyclicity was connected to Milankovitch climatic forcing. The cycles could be random events that coincidentally had an average period within the Milankovitch band. Nevertheless, this coincidence is reason enough to justify further research. Future investigations could potentially resolve this problem through the application of Fourier analysis on well constrained data sets (cf. Hays et al., 1976; Olsen, 1984; R. K. Goldhammer, P. A. Dunn and L. A. Hardie, pers. comm., 1986).

Successful documentation of a Milankovitch frequency distribution for cyclic shallow-water platforms would have several major implications, including (1) a solution for the problem of what drives platform cyclicity, (2) a new method for calculation of the duration of generally nondatable Proterozoic cyclic platform sequences, and (3) establishment of a tool for investigations of possible systematic changes in the values of Milankovitch frequencies that might relate to long-term secular evolution of celestial-mechanical relationships.

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