Modeling of tidal rhythmites using modern tidal periodicities and implications for short-term sedimentation rates

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Abstract Within Carboniferous strata cyclical variations in lamina thickness have a modern counterpart in tidal systems. These lamina thickness cycles can be equated to several types of neap-spring periodicities and longer-term seasonal periods. The various hierarchies of cycles within the ancient tidal deposits can be modeled using modern tidal station data. This type of fine-scale modeling indicates how the various tide-producing parameters of the earth-moon-sun system can be encoded in ancient tidal deposits. Based on relationships of lamina cycles to known tidal periods, inferred cycle periods indicate that such sections underwent rapid, localized, vertical accretion. Large discrepancies are evident when such short-term rates are compared to long-term rates of formation-level accumulation. Such comparisons indicate that long-term accumulation rates are many orders of magnitude slower than actual rates of deposition produced by tidal sedimentation.

Small-scale cycles occur within tidally dominated depositional environments. These cycles, considered essentially geologically instantaneous, are preserved within the stratigraphic record. In the finest scale cycle the twice daily and daily rise and fall of the tides are related to the rotation of the earth. A longer duration cycle is the approximately two-week, or neap-spring, cycles that occur twice during a lunar orbit (lunar month of 29.5 days). Three lunar orbital parameters affect neap-spring cycles. Of longer duration are seasonal and yearly cycles. In modern tidal systems slight variations in sea level, which can be as great as 1 m (3 ft), occur in half-yearly and yearly cycles. Such cycles are related in part to astronomical parameters and to seasonal climate.

A similar range of cycles was recognized in ancient tidal sequences and can be equated to subdaily to yearly tidal cycles. In ancient tidalites this range of cycles includes sedimentation rates of millimeters per day to meters per year. Cycles that are apparently longer than yearly exist within ancient tidal sequences; however, the exact cause of these cycle durations is problematic. Nonetheless, such problems in interpretation of cause and duration are not restricted to tidal sequences but are pervasive in delineation and modeling of most long sedimentary sequences.

Because tidal cycles are strongly developed and persistent and have sinusoidal periodicities, they can be modeled readily. And because the causative mechanisms and the exact periods of modern tidal cycles are known, the modeling is probably among the most reasonably constrained that can be performed on a geologic system. In addition, direct measurements of short-term sedimentation rates are possible using tidal cyclicity. These sedimentation rates can be contrasted with long-term accumulation and preservation rates. Such comparisons indicate a highly punctuated stratigraphic record in areas of tidally controlled sedimentation.

Modern tidal periodicities

Height variability and periodicities of modern tides are subject to a variety of controlling parameters. Foremost among these parameters are the gravitational effects of the moon and the lesser gravitational effects of the sun, which control the tides and relate them to the phases of the moon (synodic month) (fig. 1A), the declination of the moon (tropical month) (fig. 1B), and the distance of the moon from the earth (anomalistic month) (fig. 1C). The various effects of these periodicities on rhythmites have been discussed by Archer et al. (1990). Because of the composite interaction of these astronomical bodies with regional and local geographic and climatic effects, accurate tidal prediction involves empirical, not theoretical, considerations. Computation of tidal prediction tables [e.g., NOAA (1988)] requires the accumulation of 19 years of hourly recorded tidal data for any given station. After these data have been accumulated, harmonic analyses are used to resolve the numerous periods, which are then used to predict future tides. Despite the obvious complexity of modern tidal systems, some investigations of ancient tidal systems have failed to take the myriad complexities into account.

To understand the earth-moon dynamics involved in the deposition of tidal rhythmites, I have analyzed tidal data from several modern stations. Because of the paleogeographic location of the Carboniferous tidal rhythmites discussed here, which was near the paleoequator [see Kvale et al. (1989)], I selected stations from tropical and near-equatorial positions. For the following analyses, a three-year period for three stations was used. The stations represent a simplified spectrum from a nearly pure diurnal (one tide per day) system [Do Son, Vietnam (fig. 2A)] to a nearly pure semidiurnal (two tides per day) system [Kolaka, Sulawesi (fig. 2C)]. In addition, I considered an intermediate system, a mixed, predominantly diurnal system [Barito River, Borneo (fig. 2B)].

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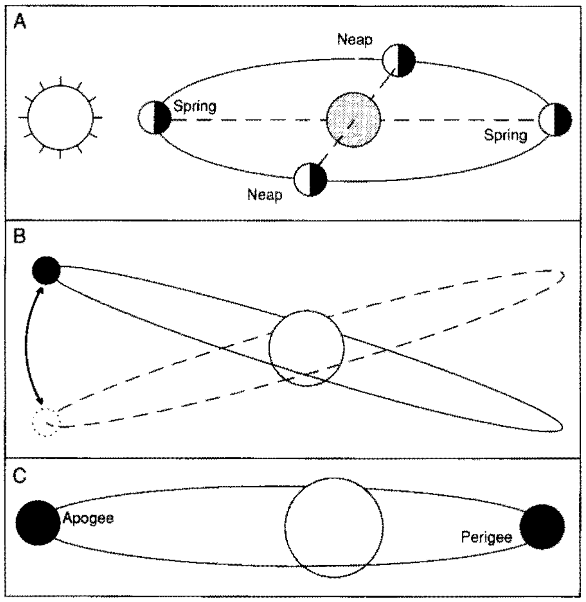

Figure 1. Main lunar periods that affect tidal heights. (A) Synodic half-month is related to lunar phases with a period of 14.77 days, which is the time between new and full moons. (B) Tropical half-month is related to lunar declination with a period of 13.66 days, which is the time required for the moon to range from a maximum northerly declination to a maximum southerly declination. (C) Anomalistic month is related to lunar distance from the earth with a period of 27.55 days (perigee to perigee).

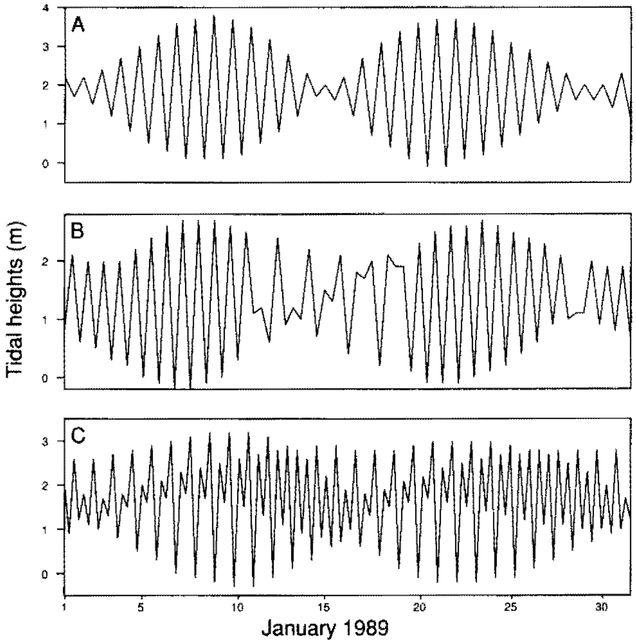

Figure 2. Predicted tidal patterns from modern equatorial stations [from data in NOAA (1988)]. (A) Do Son, Vietnam (lat. 20°40′ N., long. 106°49′ E.), exhibiting a predominantly diurnal system. (B) Barito River, Borneo (lat. 3°34′ S., long. 114°25′ E.), exhibiting a mixed, predominantly diurnal system. (C) Kolaka, Sulawesi (lat. 4°4′ S., long. 121°36′ W.), exhibiting a predominantly semidiurnal system.

Examination of the data indicates the strong development of neap-spring cycles (fig. 2) within the various tidal systems. Controlling factors include both synodic periodicities in semidiurnal systems and tropical periodicities in diurnal systems. Nonetheless, both tropical and synodic effects result in essentially the same cyclicity. Effects of lunar distance (anomalistic month) result in an inequality in heights of tides between successive neap-spring cycles. These effects are manifested by both diurnal and semidiurnal systems.

In addition to the various lunar orbital cycles, a number of longer-term periodicities exist, some of which include periods as long as thousands of years (Macmillan, 1966; Nio and Yang, 1989). However, of interest here are cycles with a seasonal or yearly periodicity. Half-yearly tidal cycles are related to the earth's axial tilt, which results in maximum solar declination during the solstices and minimum solar declination during the equinoxes. This cycle, with a period of 182.6 days, results in a variation in maximum tidal range and tidal height during the year. Such sea-level variations are enhanced by yearly climatic variations and fluctuations in temperature, air pressure, and wind direction, and all can be combined to produce a significant and systematic variation in sea level (fig. 3). Thus tidal patterns in such areas exhibit yearly fluctuations in tidal height superimposed on all the previously discussed smaller-scale patterns.

Ancient tidal rhythmites

Detailed analyses of millimeter-scale laminations within tidal rhythmites from Pennsylvanian strata of Kansas, Colorado, and Indiana reveal a hierarchy of recognizable cycles (Kvale et al., 1989; Archer and Kvale, 1989a) (fig. 4). These cycles are manifested by systematic changes in lamina thickness. Cycles contained within rhythmites can be directly correlated with modern neap-spring cycles (fig. 5). It should be noted that a neap-spring cycle includes not only a cycle that is related to lunar phase (synodic month) but also modulations of this cycle by the lunar tropical and anomalistic months [see Archer et al. (1990)].

The earliest works on the sedimentologic representation of neap-spring cycles include those by Visser (1980) and Allen (1981). In the Carboniferous of the Illinois basin, neap-spring cycles have been documented in a variety of siliciclastic systems, including shales (Kvale and Archer, 1989, 1990), siltstones (Archer and Kvale, 1989a; Kvale et al., 1989), and sandstones (Archer et al., 1989). In addition, neap-spring cycles have been documented in Mississippian carbonates (Brown et al., 1990).

Consistency of these patterns and of even larger-scale, apparently yearly cycles, through as much as 6 m (20 ft) of vertically continuous section in siltstones, indicates a strong

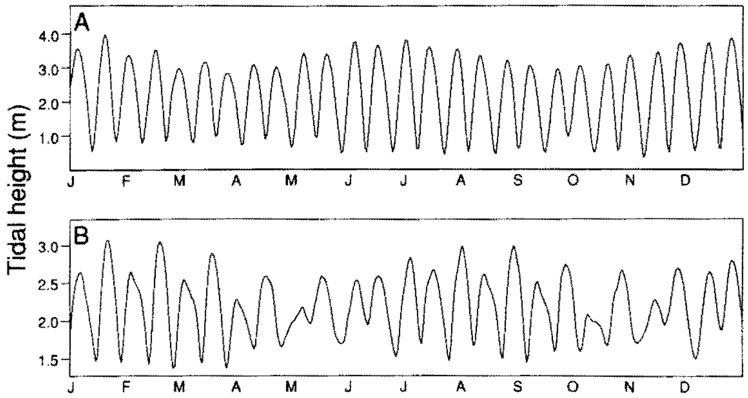

Figure 3. Yearly envelope of high tides at (A) Do Son, Vietnam, and (B) Kolaka, Sulawesi, for 1988. Tides at Do Son are lowest during equinoxes and highest during solstices; seasonal tidal variation at Kolaka exhibits a significant offset from equinoctial and solstitial control, probably reflecting regional climatic fluctuations.

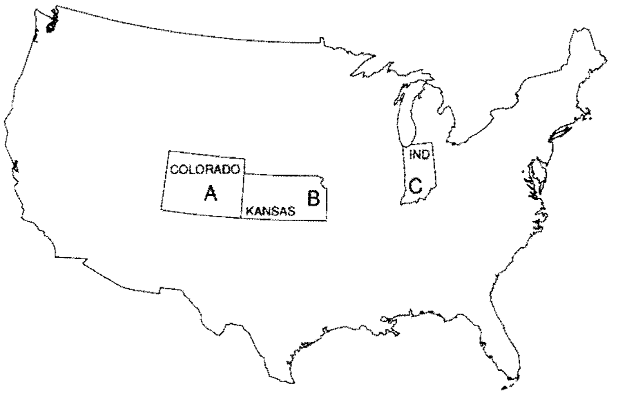

Figure 4. Location of examined Carboniferous tidalites. (A) Glen Eyrie Shale Member, Fountain Formation, near Colorado Springs, Colorado (NWSE sec. 32, T. 13 S., R. 67 W.). (B) Lawrence Shale near Lawrence, Kansas (Lone Star spillway, SESW sec. 11, T. 14 S., R. 18 E.). (C) Locations of comparable sections including the Salem limestone (Brown et al., 1990), the Hindostan whetstone of the Mansfield Formation (Kvale et al., 1989; Archer and Kvale, 1989), and the Brazil Formation (Kvale and Archer, 1990) of southern Indiana.

extrinsic control on sedimentation (fig. 6). Occurrence of these apparently yearly cycles can be related to the seasonal and/or yearly fluctuations in sea level caused by astronomical and climatic variability (see fig. 3). Archer and Kvale (1989a), Fishbaugh et al. (1989), and Kvale et al. (1989) have discussed seasonal and yearly cycles within tidal deposits of the Illinois basin. In general, these siliciclastic tidal rhythmites were deposited in similar depositional settings. These similarities include deposition on coals and development of the best cycles in the first few meters above the coals. Higher in the tidalite sections, laminae are commonly disrupted either by erosive contacts or by bioturbation. Further details on the sedimentology of sections from the Illinois basin are given by Kvale and Archer (1989, 1990) and Kvale et al. (1989).

Modeling

Modern tidal station data [such as the predictive data prepared by the NOAA (1988)] can be used to model tidal sedimentation. The most direct approach is simply to equate the thickness of a sedimentologic unit to the height of a high tide. Sedimentation during tidal fluctuations is related to a number of factors, including flow velocity, duration of flow above critical velocities, sediment particle size, availability of sediment, and duration of subaerial exposure (if any). Nonetheless, in a general way these factors are proportional to tidal height. By using tidal heights, one can synthesize artificial rhythmic tidalites by generating a simulated series of stacked laminae in which individual lamina thicknesses are proportional to tidal height. Although there are many ways to construct such proportions, a simple linear relationship between tidal height and lamina thickness generates synthetic tidalites that are similar to their ancient counterparts (fig. 7). Examination of synthetic tidalites indicates that neap-spring cycles are most clearly expressed in tidalites generated from diurnal tidal data (fig. 7A), whereas those generated from semidiurnal data show more complex and less obvious neap-spring cycles (fig. 7C).

In the following discussion I compare some ancient rhythmic tidalites with models based on modern tidal data. This discussion is concentrated on apparently diurnal tidalites from Kansas and Colorado. Patterns within diurnal tidalites from the Illinois basin have been described by Kvale and Archer (1989, 1990), and patterns from semidiurnal tidalites have been described in detail by Archer and Kvale (1989a) and Kvale et al. (1989).

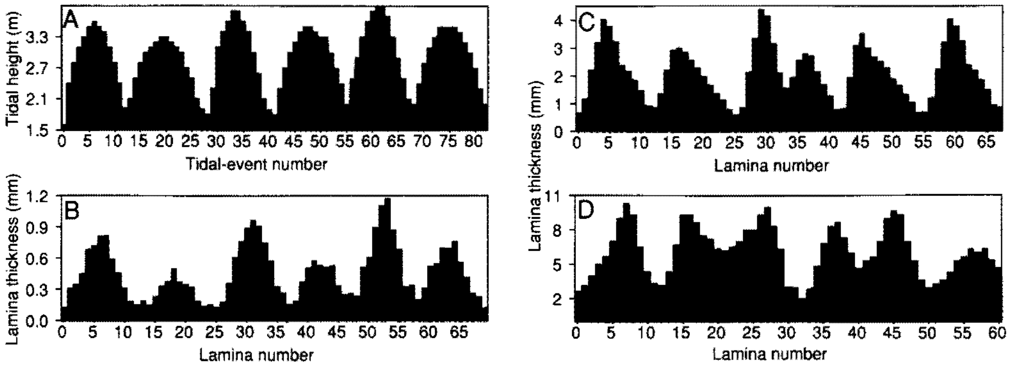

Figure 5. Histograms based on modern diurnal (one tide per day) systems and lamination thickness in rocks. (A) Tidal curve from Do Son, Vietnam. (B) Precambrian Elatina formation (Sonett et al., 1988; Williams, 1989). (C) Laminated mudstones from the Brazil Formation, southern Indiana (Kvale and Archer, 1990). (D) Laminated fine-grained sandstones from the Glen Eyrie Shale Member, Fountain Formation, Colorado.

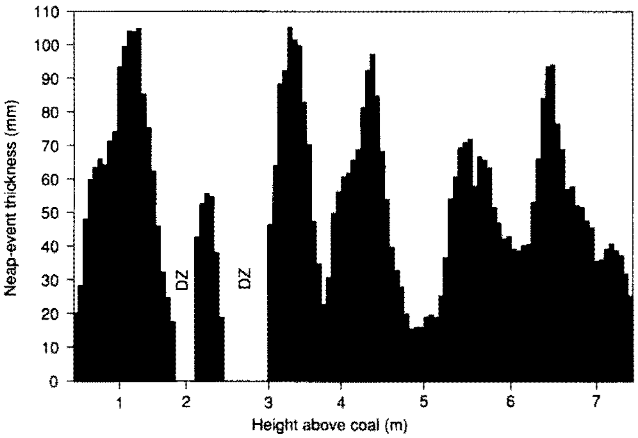

Figure 6. Large-scale cycles based on thickness of lamination in rocks interpreted as neap-spring cycles from the Hindostan whetstones of southern Indiana [adapted from Archer and Kvale (1989a)]. These cycles, which range up to 1 m (3 ft) in thickness, appear to reflect yearly sedimentation. DZ indicates disturbed zones that contain laminae contorted by soft-sediment deformation.

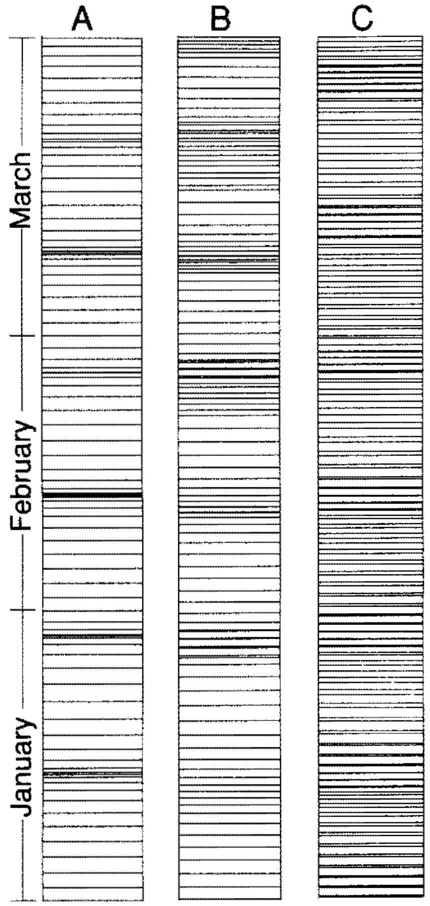

Figure 7. Artificial rhythmic tidalites generated using modern tidal data. Vertical spacing between successive laminae is proportional to tidal heights, as illustrated in fig. 2. Based on 1988 tidal data from (A) Do Son, Vietnam, (B) Barito River, Borneo, and (C) Kolaka, Sulawesi. Neap-spring cycles are clearly simulated by the diurnal system at Do Son but are less clearly developed within a semidiurnal system such as Kolaka.

Within gray shales of the Lawrence Shale of Kansas, well-developed tidal rhythmites occur locally above the upper Williamsburg coal. The stratigraphy and general depositional environment of this formation have been detailed by Rutan (1980). The coal that underlies the tidalites has a low sulfur content, one of the lowest in Kansas, and is unusual because most Kansas coals have extremely high sulfur values (Brady et al., 1976). The association of a gray shale roof and a low-sulfur coal has been long known from studies conducted in the Illinois basin (Gluskoter and Hopkins, 1970); however, the association of tidal rhythmites in gray shale with the occurrence of low-sulfur coal was documented recently (Kvale and Archer, 1989, 1990). In addition, the gray shales in the Lawrence Shale contain well-preserved plant fossils in sideritic concretions and thus share a geochemical and paleoecologic similarity with other gray shales that occur above low-sulfur coals (Baird et al., 1986). More detailed field-based analyses are needed to further delineate the similarities and differences among these gray shale lithofacies; however, the number of apparent similarities is striking.

Direct comparisons can be made between lamina thickness cycles observed in shales of the Lawrence Shale (fig. 8) and synthetic rhythmites based on tidal data recorded at Do Son, Vietnam (fig. 7A). Both the shales and the synthetic tidalites exhibit similar cycles in lamina thickness, and, where the laminae are thin, it becomes difficult to delineate individual tidal events. Thus, based on the similarities of the cyclicity, one can reasonably interpret the depositional environment of the shales of the Lawrence Shale.

More extensive work has been performed on laminated sandstones within the Glen Eyrie Shale Member of the Fountain Formation exposed near Colorado Springs, Colorado. The sedimentology and stratigraphy of the tidalite unit have been presented by O'Connell (1981). In general, the Glen Eyrie tidalite is similar to other Carboniferous tidalites because the laminated sequence directly overlies a coal, is well laminated directly above the coal, and becomes more bioturbated and possesses more fine-scale erosional features beginning several meters above the coal.

The Glen Eyrie tidalite contains three readily recognizable, hierarchical cycles. For purposes of discussion, these will be referred to as (1) macrobands, which are decimeters thick; (2) mesobands, which are 0.5–3 cm (0.2–1.2 in.) thick; and (3) microbands, which are millimeters thick. Macrobands and mesobands are readily apparent in outcrops (fig. 9A), and in polished slabs the occurrence of microbands within mesobands becomes apparent (fig. 9B). By analogy with the tidal systems previously discussed, the mesobands appear to represent neap-spring cycles, whereas the microbands appear to be analogous to daily tidal cycles. The origin of the macrobands is more problematic, but, based on the modeling described later, they may represent seasonal sedimentation.

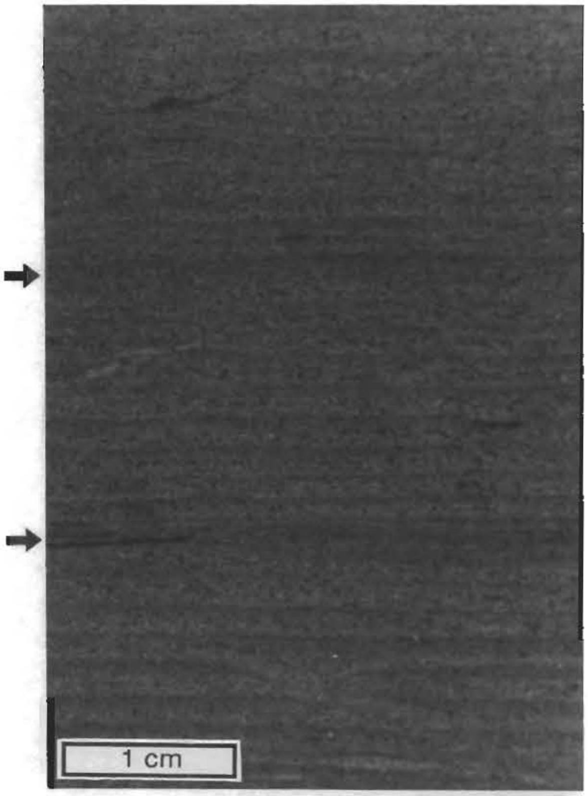

Figure 8. Polished slab of Lawrence Shale illustrating lamina thickness cycles interpreted as neap-spring tidal cycles. Arrows indicate lamina thickness minima that correspond to neap-tidal events.

Because the cyclicity resembles a diurnal tidal system, the analyses presented here compare the Glen Eyrie cycles to the diurnal system that occurs at Do Son, Vietnam. A plot of tidal flux at Do Son from vernal equinox to vernal equinox indicates higher tides during the solstices (June and December) and lower tidal maxima during the equinoxes (March and September) (fig. 10A). This variance in tidal maxima amounts to 50 cm (20 in.) during a year, which in a low-slope, low-energy coastline could amount to considerable lateral displacement of the intertidal-supratidal boundary. If the Glen Eyrie tidalites were formed in a high intertidal setting, they may have been exposed and/or not deposited for a significant part of the year. Conversely, if the tidalites were formed subtidally, too little water movement may have occurred during the equinoctial seasons to result in sedimentation that would produce recognizable laminae. Of course, many other scenarios can be hypothesized. The point is that seasonal variations in tidal heights and their effects on sedimentation are reasonable inputs to the model.

Given the flux in seasonal tidal heights for a system such as that expressed at Do Son, a cutoff line can be superimposed on the tidal curve (see fig. 10A). This cutoff can be related to

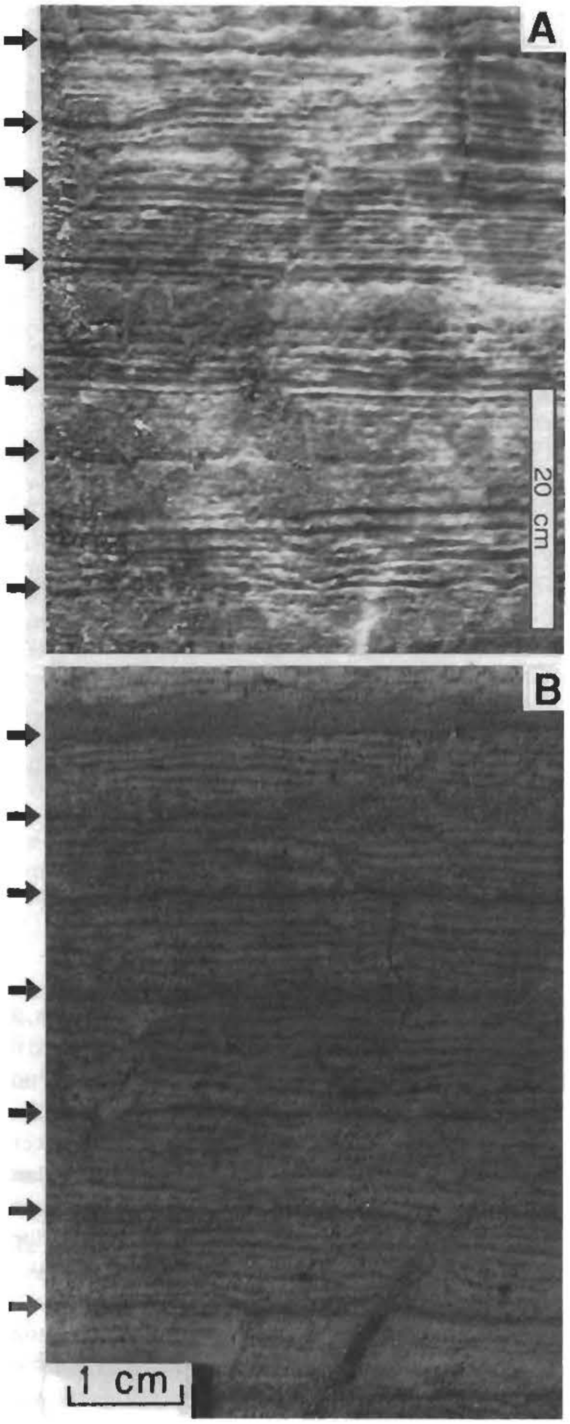

Figure 9. Field photographs of Glen Eyrie Shale Member of the Fountain Formation exposed near Colorado Springs, Colorado. (A) Macrobands (marked by arrows) in weathered exposure showing internal mesobanding. (B) Polished slab of one macroband illustrating mesobands, which are delineated by darker, more clay-rich laminae (marked with arrows). This level of cyclicity corresponds to inferred neap-spring tidal cycles. Millimeter-scale microbands within mesobands are interpreted as the product of single tidal events.

the factors described and can be conceptualized as a position within the intertidal zone or an indicator of the minimum flow velocities necessary to result in sand movement, sedimentation, and lamina development. This cutoff concept is similar to the critical transport model discussed by Allen (1981). Given such an arbitrary cutoff, only those events that exceed this criterion will result in a preserved, recognizable sedimentologic feature, which in this case is a thin lamination. Depiction of the tidal events that exceed the cutoff can be presented in a histogram format (fig. 10B) and compared to other laminae histograms (such as fig. 5). Thus fig. 10B models the potential of a preserved sedimentologic record created by using a relatively high cutoff value for the tidal system at Do Son (fig. 10A). By using the cutoff histogram, the Do Son data can be compared to lamina thickness distributions observed in a single macroband from the Glen Eyrie tidalite (fig. 10C). With this model a macroband may represent half-yearly, equinox-to-equinox sedimentation. In such a model sedimentation and preservation of neap-spring cycles and individual laminae occurred only when a critical threshold (the cutoff value) was exceeded.

For comparisons, other researchers have presented observations and interpretations of seasonal sedimentation within modern tidal systems (van den Berg, 1981). A model invoking yearly fluctuation in fluvial input for a complete Precambrian tidalite has been suggested by Sonett et al. (1988). Although our understanding of ancient tidal sedimentology is still incomplete, it appears that such systems developed within cratonic settings with high preservation potential of short-term events.

Sedimentation rates

One of the more intriguing aspects of tidalites is their record of measurable rates of short-term sedimentation and high degree of preservability of fine-scale time. In general, tidalite cycles represent the low end of a spectrum of cyclic sea-level fluctuations that can be recorded in sedimentary rocks (fig. 11). Preservation of semidiurnal and diurnal sedimentation events over time spans of months (Visser, 1980; Allen, 1981; Kreisa and Moiola, 1986) and even years (van den Berg, 1981; Sonett et al., 1988; Williams, 1989; Kvale et al., 1989) greatly influences our concepts of the completeness of the rock record. Previous discussions of stratigraphic completeness (Sadler, 1981; Sadler and Dingus, 1982; Anders et al., 1987) generally concentrated on hundred-year and thousand-year time periods. Conversely, in tidalite-bearing sequences, not only have detailed multiyearly records of nearly continuous diurnal and semidiurnal sedimentation events been preserved but also extremely high rates [as much as 1 m/yr (3 ft/yr)] of sedimentation have been documented (Baird et al., 1986; Broadhurst, 1988; Kvale et al., 1989). Although it appears that such rates were achieved only locally and may be

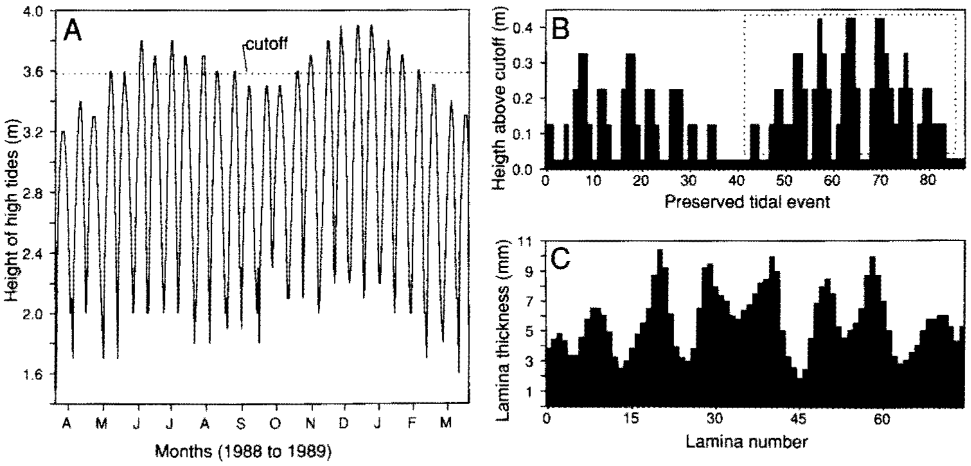

Figure 10. Comparison of Glen Eyrie tidal rhythmites to modern tidal data from Do Son, Vietnam. (A) Equinox-to-equinox tidal-range curve from Do Son illustrating higher tides during solstices. (B) Record of individual tidal events that exceeded the cutoff threshold diagrammed in part (A). Only tidal events with heights larger than the cutoff in part (A) are depicted in part (B). (C) Lamina thickness distribution from Glen Eyrie sandstone (illustrated in fig. 9B). Tidal patterns can be compared to boxed area in part B; the cycles expressed in the Glen Eyrie suggest tidal deposition during the highest solstitial tide and thus record only partial tidal cycles.

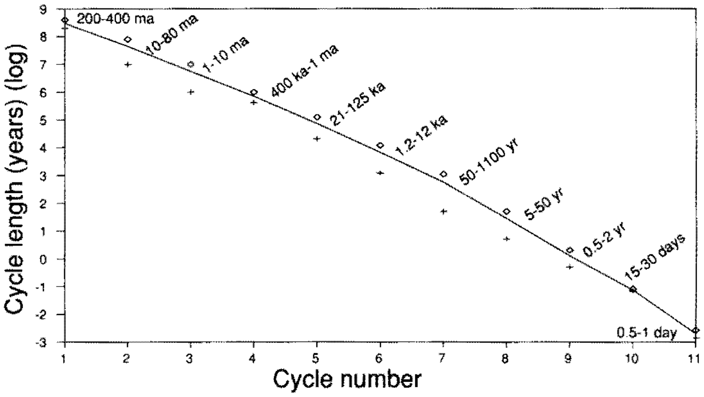

Figure 11. Spectrum of geologic cycles. Durations of higher-order cycles (first through sixth) are derived from various sequence stratigraphic sources. Intermediate-order cycles (2,250 and 250 years) are inferred. Eleven-year cycle is average sunspot cycle, and lowest-order cycles are related to tidal deposition.

related to rapid generation of accommodation space, for example, by clay and peat compaction (Kvale and Archer, 1989) or channel abandonment (van den Berg, 1981; Brown et al., 1990), the occurrence of such rates of sedimentation indicate one of the difficulties of delineation and correlation of longer-term (10,000–100,000-year), meter-thick cycles on either the local or regional scale, such as those advocated by Busch and Rollins (1984), Goodwin and Anderson (1985), and Busch and West (1987).

Comparisons can be made between tidalite-based rates of sedimentation and rates deduced for longer-term cycles ("sixth-order" and longer cycles; fig. 11). Rates of sedimentation based on detailed lamina measurements are orders of magnitude more rapid than rates derived by dividing formational thickness by formational time. For example, tidalites within the Mansfield Formation of Indiana accumulated at determinable rates of accumulation as high as 1 m/yr (3 ft/yr); however, dividing formational time (15 m.y.) by formational thickness [90 m (300 ft)] yields rates of 1 m (3 ft) per 160,000 years. [The average thickness and duration of Mansfield deposition were estimated from data by Shaver (1984); although time estimates for duration of the Carboniferous are

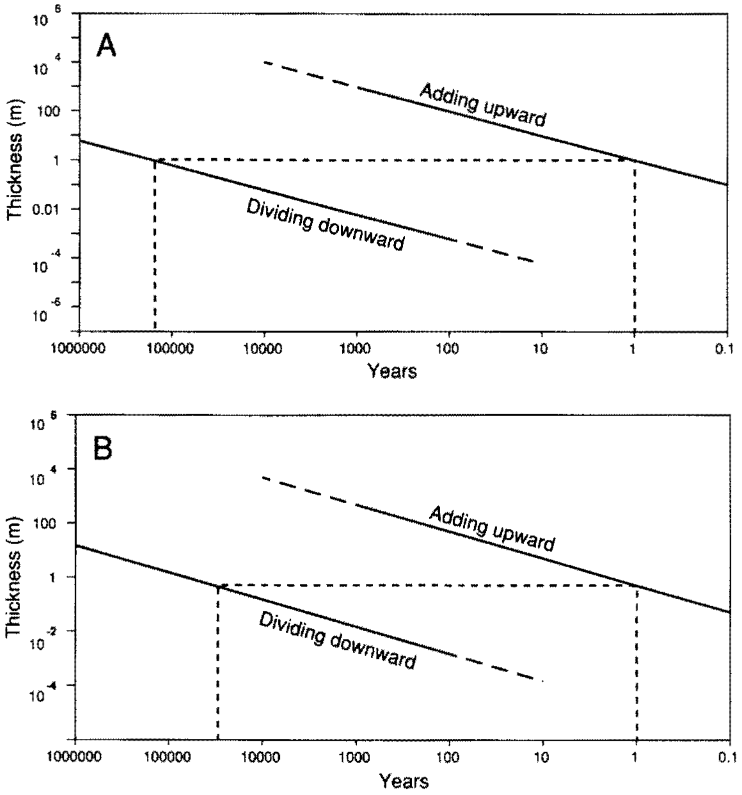

Figure 12. (A) Differences in estimating lengths of time for deposition of the Mansfield Formation (Pennsylvanian) of southwestern Indiana. The line labeled "adding upward" is based on rates of sedimentation derived from analyses of daily, biweekly, and yearly tidal cycles. Conversely, the line labeled "dividing downward" is based on average long-term rates derived by dividing total formational thickness by total formational time. For 1 m (3 ft) of sediment, the two techniques yield rates that differ by over five orders of magnitude. (B) Similar techniques applied to carbonate tidalites within the Salem limestone of Indiana (Brown et al., 1990). Comparison of results indicates that the dividing-downward technique yields long-term sedimentation rates that are orders of magnitude higher than short-term rates identifiable in the rhythmic tidalites.

highly variable (Klein, 1990), these differences do not significantly affect the comparison between long- and short-term deposition.] At least within these localized tidal deposits, formational time divided by formational thickness yields depositional rates that are many orders of magnitude slower than those indicated by detailed sedimentologic analyses (fig. 12). Such comparisons support a view of the rock record in which short-term episodes of rapid sedimentation are punctuated by long periods of nondeposition. Thus delineation of short- and long-term cycles becomes extremely problematic without reasonable sedimentologic constraints.

In addition to the small-scale (in time) cycles, the tidal systems contain a number of larger-order cycles. In all the Carboniferous sections the tidalites overlie coals and grade upward into rooted coals, signifying a transition from a marine to a terrestrial environment. The vertical distance between the lower and upper coals ranges from 3 m to 10 m (9–30 ft). A number of similar sub-Recent successions suggest, based on radiocarbon dating of peat, that the time span between peat accumulation events is of the order of several thousand years (Roep and van Regteren Altena, 1988; Dionne, 1988). Thus, given the rates of deposition that are possible within tidally influenced environments, meter-thick coal-bearing sequences can form in geologically short periods of time.

Implications for sequence stratigraphy

The Pennsylvanian system can be defined as a single synthem, or second-order cycle, that extends from the Mississippian–Pennsylvanian unconformity to the Lower Permian unconformity (Vail et al., 1977). In the United States Pennsylvanian strata have long been recognized as being cyclic or containing cyclothems (Wanless and Weller, 1932), and eustatic control has long been advocated (Wanless and Shepard, 1936). More recently, these cyclothemic concepts have been recast as third- through sixth-order sequence stratigraphic cycles and have been reported in the Appalachian basin and in Kansas (Busch and Rollins, 1984). Based on preliminary subsurface work (L. Furer, personal communication, 1989), the Mansfield Formation of Indiana, which contains tidalites (Kvale et al., 1989; Archer and Kvale, 1989a), has been divided regionally into three subdivisions, and the top of each subdivision represents a eustatic rise (L. Furer, personal communication, 1990). Because the total formational time of the Mansfield is 15 m.y. (Shaver, 1984), these sequences, which represent third- or lower-order sequence stratigraphic units, can be inferred to represent 5 m.y. Based on the approximately 30-m (90-ft) thickness of these 5-m.y. cycles, the sedimentation rate of the cycles would be 6 m (20 ft) per 1 m.y. Such long-term rates are many orders of magnitude slower than monthly and yearly rates observed in the tidalite sequences (Archer and Kvale, 1989b). Extrapolation of the short-term rates indicates that anomalously thick sequences of strata would have been produced if such rates had continued over long periods of time. Therefore numerous or lengthy periods of erosion or nondeposition existed (Dott, 1983) during the 15-m.y. time interval represented by the Mansfield Formation (fig. 12A). Similarly, tidal rhythmites within the Salem limestone of Indiana imply fast rates of short-term deposition compared to average long-term accumulation rates of the formation (fig. 12B). Localized minor unconformities probably anastomose and coalesce to form the types of sequence stratigraphic boundaries that delineate the longer-term cycles.

Conclusions

Carboniferous tidal rhythmites exhibit a variety of expressions of cyclicity in lamina thicknesses; however, modeling of rhythmite patterns using modern predictive tidal station data yields clues to the importance of the various tide-producing forces involved in rhythmite generation. Because modern tidal periodicities are well established, duration of comparable cycles in the ancient rhythmites can be closely approximated. Thus short-term rates of deposition can be readily computed and then compared to long-term, or formation-level, rates of accumulation. The great disparity in long-term versus short-term rates implies that, at least in tidally influenced systems, sedimentary sequences are potentially highly punctuated. Therefore the amount of time actually required for deposition and the time interval represented by a given stratigraphic unit are potentially vastly different. This difference is mainly due to the temporal dominance of nondepositional and/or erosional processes over actual deposition. Thus many vertical sections are characterized by short-term, rapidly accumulated sequences separated by extended periods of nonpreserved deposition. If this is generally true, then there are extreme problems with equating unit thickness to time in tidally influenced systems.

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References

Allen, J. R. L., 1981, Lower Cretaceous tides revealed by cross-bedding with mud drapes: Nature, v. 289, p. 579–581

Anders, J. H., Krueger, S. W., and Sadler, P. M., 1987, A new look at sedimentation rates and the completeness of the stratigraphic record: Journal of Geology, v. 95, p. 1–14

Archer, A. W., and Kvale, E. P., 1989a, Seasonal and yearly cycles within tidally laminated sediments—an example from the Pennsylvanian of Indiana, USA; *in*, Geology of the Lower Pennsylvanian in Kentucky, Indiana, and Illinois, Cobb, J. C., ed.: Illinois Basin Studies 1, Illinois Basin Consortium (Kentucky Geological Survey, Indiana Geological Survey, and Illinois State Geological Survey), p. 45–56

__________, 1989b, Ultimate resolution of transgressive-regressive stratigraphic units—a theoretical discussion based upon the Carboniferous of the Illinois basin: Geological Society of America, Abstracts with Programs, v. 20, p. 327–328

Archer, A. W., Kvale, E. P., and Johnson, H. R., 1990, Discussion on late Precambrian tidal rhythmites in South Australia and the history of the Earth's rotation: Journal of the Geological Society of London, v. 147, p. 401–402

Archer, A. W., Devera, J. A., Kvale, E. P., and Nelson, W. J., 1989, Stop 9, Upper Caseyville/Lower Tradewater roadcut on Interstate 57, southern Illinois—tidally influenced deposits of Early Pennsylvanian age; *in*, Carboniferous Geology of the Eastern United States, Cecil, C. B., and Eble, C., eds.: American Geophysical Union, Field Trip Guidebook T143, Washington, DC, p. 30–32

Baird, G. C., Sroka, S. D., Shabica, C. W., and Kuecher, G. V., 1986, Taphonomy of middle Pennsylvanian Mazon Creek area fossil localities, northeast Illinois—significance of exceptional fossil preservation in syngenetic concretions: Palaios, v. 1, p. 271–285

Brady, L. L., Adams, D. B., and Livington, N. D., 1976, An evaluation of the strippable coal reserves in Kansas: Kansas Geological Survey, Mineral Resources Series 5, 40 p.

Broadhurst, F. M., 1988, Seasons and tides in the Westphalian; *in*, Sedimentation in a Synorogenic Basin Complex—The Upper Carboniferous of Northwest Europe, Besley, B. M., ed.: Blackie and Son, London, p. 264–272

Brown, M. A., Archer, A. W., and Kvale, E. P., 1990, Neap-spring tidal cyclicity in laminated carbonate channel-fill deposits and its implications—Salem Limestone (Mississippian), south-central Indiana, USA: Journal of Sedimentary Petrology, v. 60, p. 152–159

Busch, R. M, and Rollins, H. B., 1984, Correlation of Carboniferous strata using a hierarchy of transgressive-regressive cycles: Geology, v. 12, p. 471–474

Busch, R. M., and West, R. R., 1987, Hierarchal genetic stratigraphy—a framework for paleoceanography: Paleoceanography, v. 2, p. 141–164

Dionne, J. C., 1988, Holocene relative sea-level fluctuations in the St. Lawrence Estuary, Quebec, Canada: Quaternary Research, v. 29, p. 233–244

Dott, R. H., Jr., 1983, SEPM presidential address—episodic sedimentation. How normal is average? How rare is rare? Does it matter?: Journal of Sedimentary Petrology, v. 53, p. 5–23

Fishbaugh, D. A., Kvale, E. P., and Archer, A. W., 1989, Association of tidal and fluvial sediments within Lower Pennsylvanian rocks, Turkey Run State Park, Parke County, Indiana: Guidebook, American Association of Petroleum Geologists, Eastern Section Meeting, 46 p.

Gluskoter, H. J., and Hopkins, M. E., 1970, Distribution of sulfur in Illinois coal; *in*, Depositional Environments in Parts of the Carbondale Formation—Western and Northern Illinois, Smith, W. H., Nance, R. B., and Hopkins, M. E., eds.: Illinois Geological Survey, Guidebook Series 8, p. 89–95

Goodwin, P. W., and Anderson, E. J., 1985, Punctuated aggradational cycles—a general hypothesis of episodic stratigraphic accumulation: Journal of Geology, v. 93, p. 515–533

Klein, G. de V., 1990, Pennsylvanian times scales and cycle periods: Geology, v. 18, p. 455–457

Kreisa, R. D., and Moiola, R. J., 1986, Signoidal tidal bundles and other tide-generated sedimentary structures of the Curtis Formation, Utah: Geological Society of America Bulletin, v. 97, p. 381–387

Kvale, E. P., and Archer, A. W., 1989, Recognition of tidal processes in mudstone-dominated sediments, Lower Pennsylvanian, Indiana; *in*, Geology of the Lower Pennsylvanian in Kentucky, Indiana, and Illinois, Cobb, J. C., ed.: Illinois Basin Consortium (Kentucky Geological Survey, Indiana Geological Survey, and Illinois State Geological Survey), p. 29–44

__________, 1990, Tidal deposits associated with low-sulfur coals, Brazil Formation (Lower Pennsylvanian), Indiana: Journal of Sedimentary Petrology, v. 60, p. 563–574

Kvale, E. P., Archer, A. W., and Johnson, H. R., 1989, Daily, monthly, and yearly tidal cycles within laminated siltstones of the Mansfield Formation (Pennsylvanian) of Indiana: Geology, v. 17, p. 365–368

Macmillan, D. H., 1966, Tides: CR Books Limited, London, 240 p.

Nio, S. D., and Yang, C. S., 1989, Recognition of tidally influenced facies and environments: International Geoservices BV, Short Course Note Series 1, Leiderdorp, Netherlands, 230 p.

NOAA, 1988, Tide tables, 1988, high and low water predictions, Central and Western Pacific Ocean and Indian Ocean: National Oceanic and Atmospheric Administration, US Department of Commerce, Riverdale, Maryland, 381 p.

O'Connell, A., 1981, Origin of the Glen Eyrie member of the Fountain Formation: A.M. thesis, Indiana University, Bloomington, 174 p.

Roep, T. B., and van Regteren Altena, J. F., 1988, Paleotidal levels in tidal sediments (3800–3635 B.P.)—compaction, sea level rise and human occupation (3275–2620 B.P.) at Bovenkarspel, NW Netherlands; *in*, Tide-Influenced Sedimentary Environments and Facies, de Boer, P. L., van Gelder, A., and Nio, S. D., eds.: D. Reidel Publishing Co., Boston, p. 215–231

Rutan, D., 1980, The petrology and depositional environments of the Pennsylvanian Lawrence Formation in eastern Kansas: M.S. thesis, University of Kansas, Lawrence, 120 p.

Sadler, P. M., 1981, Sediment accumulation rates and the completeness of stratigraphic sections: Journal of Geology, v. 89, p. 569–584

Sadler, P. M., and Dingus, L. W., 1982, Expected completeness of sedimentary sections—estimating a time-scale-dependent limiting factor in the resolution of the fossil record; *in*, Third North American Paleontological Convention Proceedings, Mamet, B., and Copeland, M. J., eds.: Geological Survey of Canada, Ottawa, v. 2, p. 461–464

Shaver, R. H., ed., 1984, Midwestern basins and arches region—correlation of stratigraphic units in North America: Chart MBA, American Association of Petroleum Geologists, Tulsa, Oklahoma

Sonett, C. P., Finney, S. A., and Williams, C. R., 1988, The lunar orbit in the later Precambrian and the Elatina sandstone laminae: Nature, v. 335, p, 806–808

Vail, P. R., Mitchum, R. M., Todd, R. G., Widmier, J. M., Thompson, S., Sangree, J. B., Budd, J. N., and Hatelid, W. G., 1977, Seismic stratigraphy and global changes of sea level; *in*, Seismic Stratigraphy—Applications to Hydrocarbon Exploration, Payton, C. E., ed.: American Association of Petroleum Geologists, Memoir 26, p. 49–212

van den Berg, J. H., 1981, Rhythmic seasonal layering in a mesotidal channel fill sequence, Oosterschelde Mouth, the Netherlands; *in*, Holocene Marine Sedimentation in the North Sea Basin, Nio, S. D., Shuttenheim, R. T. E., and van Weering, T. C. E., eds.: International Association of Sedimentologists, Special Publication 5, p. 147–159

Visser, M. J., 1980, Neap-spring cycles reflected in Holocene subtidal large-scale bedform deposits—a preliminary note: Geology, v. 8, p. 543–546

Wanless, H. R., and Shepard, F. P., 1936, Sea-level and climatic changes related to late Paleozoic cycles: Geological Society of America Bulletin, v. 47, p. 593–606

Wanless, H. R., and Weller, J. M., 1932, Correlation and extent of Pennsylvanian cyclothems: Geological Society of America Bulletin, v. 43, p. 1,003–1,016

Williams, G. E., 1989, Late Precambrian tidal rhythmites in South Australia and the history of the Earth's rotation: Geological Society of London Journal, v. 146, p. 97–111