Tides, tidalites, and secular changes in the Earth–Moon system

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ABSTRACT

Tides have been a source of inquiry since the dawn of human civilization. It has been known for millennia that the Moon is a causative agent in the formation of tides, with the observation that lunar phases often correlated to changing tidal amplitudes. The precise mechanisms underlying the formation of tides and local tidal dynamics, however, have proven difficult to elucidate. Only with Newton's theory of gravitation in the 17th century was the correlation between lunar cycles and tides partially explained. Further work by Laplace and others resulted in a more dynamic theory that more closely matched observations and allowed for better prediction of local tidal behavior. Quantitative models derived from these methods have increased in precision and complexity (particularly with the advent of the electronic computer), and have allowed new insights into the nature of tidal dynamics and tidal dissipation.

In more recent years scientists have analyzed deposits known as tidal bundles and tidal rhythmites in an attempt to extrapolate the history of tides from the geologic record. Tidal bundles are laterally accreted cyclic foreset beds separated by mud laminae. Tidal rhythmites are vertically accreted planar laminae that alternate between coarse and fine sediments forming couplets often composed of sands and muds. These deposits are characterized by bed/laminae thicknesses that vary rhythmically and preserve tidal periodicities, and are generally found in intertidal or subtidal depositional environments. The mode of deposition (e.g. sand or mud) is primarily determined by current velocity and tidal range, factors largely controlled by the tides in marginal marine settings.

Quantitative analyses of tidal rhythmites may facilitate more precise elucidation of tidal periodicities encoded in the rock record. The partial reconstruction of the history of lunar recession from existing data and analyses indicates that the Earth is presently experiencing a high rate of tidal dissipation. Further data obtained from ancient tidal proxies may prove essential in constraining models of tidal dissipation, thereby revealing the mechanisms and dynamics present in the dissipation process controlling secular changes in the length of day and lunar orbit.

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1. Introduction

The earliest humans, in their wonder of the natural world, are known to have observed the periodic changes of the lunar profile and rhythmic pulse of the tides. Numerous lunar and tidal myths and associated deities are recorded throughout the bulk of written history as evidence of interest in these ever-present phenomena (Krupp, 1992). This interest eventually resulted in a realization of the synergy present between tides and the lunar orbit. Newton, writing his Principia Mathematica, very specifically addressed the problem, and used his results as evidence in support of his theory of gravity. Soon after, Edmund Halley employed ancient and modern eclipse data in recognizing that the lunar orbit was inconstant and accelerating with the passage of time (Stephenson, 1997). Subsequent researchers in the 18th and 19th centuries began to relate the lunar orbital acceleration to a slowing of the Earth's rotation (Lambeck, 1980). These findings represented a fundamental shift in the way the Earth–Moon system was perceived. It was no longer seen as an orbitally fixed pair of monoliths, but, rather, an evolving system with a variable history and uncertain future. Within the next century, mechanisms were proposed that, in basic form and function, persist to this day. Chiefly among these is Kant's hypothesis that the Moon and the Sun induce oceanic tidal bulges on the Earth's surface (Kant, 1754). As the Earth rotates “under” these bulges, a dissipation of energy and angular momentum is realized. Subsequent researchers, such as G.H. Darwin extended these results to demonstrate that energy and angular momentum are transferred from Earth's rotation to the lunar orbit, slowing the Earth's rate of rotation while accelerating the Moon's orbit. These ideas formed the fundamental basis of all descendant Earth–Moon system studies. A comprehensive overview of these developments is provided by Stephenson (1997).

In the 20th century the problem received renewed interest as new experimental data were realized. Analysis of daily and monthly growth bands present on Paleozoic and Mesozoic invertebrate fossils revealed changes in the lengths of the day and month and offered a new line of evidence in the field (e.g. Wells, 1963; Berry and Barker, 1968). This period also saw the emplacement of cubic re-ectors on the lunar surface by several Apollo and Luna missions for the purpose of measuring lunar laser ranging (Calame and Mulholland, 1978). This has allowed determination of quantities such as the number of days in a month, the number of hours in a day, and the positions of the Sun and the Moon in the sky. A seminal breakthrough and a first approximation of tidal forces, makes use of simplifying assumptions that render its predictive capabilities of real world tides largely ineffective. Subsequent work on the topic sought to explain the more localized dynamics of tides in terms of tidal waves with characters that are dependent on position, local bathymetry, and other factors. These refinements have been provided by Laplace, Euler, Kant, Thomson, and others (Section 2.3). Wylie (1979) and Cartwright (2001) have provided a thorough treatment of the history of tide-related inquiry.

2. Background and theory

2.1. Historical interest and observations

A 30,000 year-old reindeer bone gouged with a series of holes by a Cro-Magnon indicates the conscious recognition that intelligent life on Earth has given the presence of the Moon (Wylie, 1979). The bone, interpreted as recording the passage of the Moon for more than 2 months, is one of many such evidences. Pliny, a Roman born in 23 A.D., and killed by the eruption Mt. Vesuvius, described monthly variations in tidal height (neap-spring cycles) and recognized the relation between these variations and the Sun and the Moon. In his Historia Naturalis he writes, “Much has been said about the nature of waters; but the most wonderful circumstance is the alternate flowing and ebbing of the tides, which exist, indeed, under various forms, but is caused by the Sun and the Moon” (Clancy, 1968).

The limited observations made by the ancients, while useful (particularly to sailors and religious figures), were not seriously extended until the 17th century. It was then that Isaac Newton published his equilibrium theory of tides. The equilibrium theory, while a seminal breakthrough and first approximation of tidal processes, makes use of simplifying assumptions that render its predictive capabilities of real world tides largely ineffective. Subsequent work on the topic sought to explain the more localized dynamics of tides in terms of tidal waves with characters that are dependent on position, local bathymetry, and other factors. These refinements have been provided by Laplace, Euler, Kant, Thomson, and others (Section 2.3). Wylie (1979) and Cartwright (2001) have provided a thorough treatment of the history of tide-related inquiry.

2.2. Theory of tides

Equilibrium tidal theory, proposed by Newton, assumes an Earth covered in a uniform depth of water, and provides a simple, yet feasible explanation of the astronomical factors that control ocean tides and the genesis of their corresponding components. Because the Moon is over 1.23% of the Earth's mass and is relatively close to Earth (about 60 Earth radii), it is said that the Earth and Moon form a binary planet. The gravitational potential from the Moon is sufficient to induce solid-Earth and oceanic bulges on opposite sides of the Earth. The Sun, while millions of times more massive than the Moon, is located nearly 400 times further from the Earth than the Moon. Because the gravitational potential increases linearly with mass but decreases with the cube of the distance between two bodies, the Sun contributes only 46% of the tide-producing force that the Moon provides. The process by which this is accomplished is best explained if the rotation of the Earth is momentarily neglected, and only the rotation of the Earth's center around the center of gravity of the Earth–Moon system is considered (Clancy, 1968). This rotation results in centripetal forces at every location in the Earth that point in the direction of that location's particular center of rotation (Fig. 1). These centripetal forces are generally different in direction and magnitude than gravitational forces (directed at the Moon's center of mass); Only
two points ($P_1$ and $P_2$), occurring along a line connecting them to the center of the Moon and on opposite ends of the Earth, will have centripetal and gravitational forces in the same direction (Fig. 2). The difference between the gravitational force and required centripetal force causes tidal bulges. At $P_1$, the gravitational force is less than the centripetal force and results in a net effective force (often known as centrifugal force) in a direction away from the Moon. This net effective force arises from Newton’s third law, which states that for every force there is an equal and opposite force somewhere in the system. This opposite force, however, does not act on the same object as the centripetal force, otherwise all forces would cancel and there would be no accelerations. On the side facing the Moon the centripetal force is less than the gravitational force and another tidal bulge is created (Fig. 2). The Earth spins through these bulges, resulting in lunar and solar-induced semidiurnal tides (called the $M_2$ and $S_2$ tides, respectively) which also show periodic variations in intensity due to the lunar and solar positions relative to the Earth (Fig. 3). Thus, the dominant astronomical period in a system largely determines the amplitude of the tidal bulges and, thus, the tides.

Equilibrium tidal theory makes several assumptions that require refinement. The theory assumes that 1) water interacts gravitationally, but does not possess inertia (i.e. gravitational response of oceans is instantaneous), 2) all motion except the rotation of the Earth–Moon center is discounted, thus, discounting geostrophic effects associated with Earth’s orbit and axial rotation, and 3) the Earth is covered in a uniform depth of water, which eliminates complications arising from continental configurations and bottom friction.

Dynamic tidal theory, first formulated by Laplace and subsequently refined, incorporates the complexities of tidal dynamics owing to shoreline geometry, bathymetry, and geostrophic effects. As waves approach the shore they are transmitted, refracted, and reflected in a manner determined by the geometry of the marginal marine setting. Deflections arising from the Earth’s rotation, such as the Coriolis Effect, cause east–west and north–south propagation of tidal waves. These orthogonal deflections result in a net elliptical path of propagation. This is confirmed by empirical data revealing rotation of cotidal lines (lines where high tides occur simultaneously) around an amphidromic point (where cotidal lines intersect). The complexity of these effects, which only computationally intensive models can approach, yields a heterogeneous global network of amphidromes and tides (Fig. 4).

The tide-producing potential at a given location can be evaluated when the positions and distances of the Moon and Sun relative to Earth are tabulated. The rather concise resulting expression for the potential can be expanded via the use of trigonometric identities into a sum of cosines. The developments of Fourier in the arena of wave analysis proved pivotal in surmising the various components of the total tide. In the Fourier expansion a continuous waveform can be expressed as a sum of sine and/or cosine waves (usually, cosines are employed in tidal theory so that the phases may be determined more readily). Accordingly, empirical tidal height records for a particular location can expressed as a superposition of harmonic constituents similar to the expansion of the tide-producing potential:

$$h(t) = h_o + \Sigma A_i \cos(2\pi f_it - \phi_i)$$

where $h_o$ is the average tide height (or some other datum), $A_i$ is the amplitude, $f_i$ is the frequency, $\phi_i$ is the phase of the component, and $t$ is the time. The amplitudes and phases of the constituents in Eq. (1) can be found via least squares or harmonic analysis. There are over 390 harmonic constituents composed of 6 fundamental frequencies (corresponding to actual luni-solar periods) (Doodson, 1921). There are seven predominant constituents in most systems. A thorough discussion of tidal theory and prediction is provided by Pugh (1987).

### 2.3 Luni-solar periods

Tidal height amplitudes are modulated at a range of temporal scales ranging from daily to millennial. The recognition of a tidal regime as exhibiting daily (diurnal), twice-daily (semidiurnal), or a combination of daily and twice-daily deposition throughout a tidal cycle is an important distinction that is closely related to the dominant luni-solar periodicity. The form factor equation defines the regime and is given as

$$F = (K_1 + O_1) / (M_2 + S_2)$$

where $K_1$ and $O_1$ are the primary constituents in diurnal systems and $M_2$ and $S_2$ are the primary constituents in semidiurnal systems. In the case where $F<0.25$, the system is classified as semidiurnal. If $0.25<F<3.00$, the system is mixed, and if $F>3.00$, the system is diurnal (see discussion in Defant, 1961).

In semidiurnal systems, the inequality between successive high tides is known as the ‘diurnal inequality.’ The diurnal inequality arises due to the effects of lunar declination and approaches zero as the Moon’s declination with respect to the equator approaches zero. At lower frequencies, but greater amplitudes are the various neap-spring cycles, which are lunar or luni-solar half-months.

The synodic month is the time required for the Moon to cycle through its phases (e.g. time elapsed between successive full Moons). Syzygy (when the Earth, Moon, and Sun are in alignment) occurs during full Moon or new Moon, disregarding lag effects. During syzygy in a synodically driven system, the tides become highest (spring tides). Near times of quadrature (when the Moon is 90° from the Sun relative to Earth) the tides become lowest (neap tides). The synodic
The period is currently 29.53 solar days (this is the average value, as fluctuations are induced by the Earth’s elliptical orbit around the Sun). Half the synodic period, or 14.76 solar days, is a neap-spring period in a synodically driven system. Synodically driven systems produce semidiurnal tides with the $M_2$ and $S_2$ constituents being dominant.

The tropical period is the time required for the Moon to move from a given declination and back, currently 27.32 solar days. Diurnal systems (one tide per day) are driven by the tropical period. The $O_1$ (diurnal constituent due to lunar declination) and $K_1$ (diurnal constituent due to lunar and solar declinations) constituents are amplified in these systems while the $M_2$ and $S_2$ constituents are damped, often owing to shallow shelf depths and restricted gulf or bay access from open waters. Much of the Gulf Coast of North America experiences diurnal tides for these reasons.

The anomalistic period is the time it takes the Moon to achieve successive perigean distances in its elliptical orbit. The current duration of the anomalistic period is 27.55 solar days. This cycle, in part, accounts for the difference in amplitude between the first spring tide of the month, and the second. This semi-monthly inequality is enhanced when apogee and perigee are in phase with the synodic or tropical periods (Kvale, 2006).

The sidereal period is the actual orbital period of the Moon around the Earth relative to fixed celestial references. Currently, the sidereal month is 27.32 solar days. It is interesting to note that the period from
new Moon to new Moon does not denote one revolution of the Moon about the Earth. Because the Earth is moving in its orbit around the Sun, the Moon orbits more than 360° from new Moon to new Moon. It is for this reason that the synodic month is longer than the sidereal month. The number of lunar or solar days in the sidereal month is not extracted directly from the tidal proxy records, although conversions utilizing the synodic and tropical months have been proposed (Runcorn, 1979; Kvale et al., 1999).

Longer-term periods, while generally of smaller magnitude, also have significant effects on tidal amplitudes. This is evident in Doodson’s decomposition, whereby three of the six fundamental frequencies used in reconstructing all 390 tidal constituents that comprise the total tide possess periods of 8.85 years, 18.61 years, and 20,940 years. The 8.85 year period is the lunar apsides cycle, which is due to the changing orientation of the lunar orbital ellipse. The time required for the line connecting perigee and apogee in the lunar orbit to occur with the same orientation again is one lunar apsides cycle. The 18.61 year period denotes the lunar nodal cycle, which marks one revolution of the precessing lunar nodes (where the lunar orbit intersects the ecliptic, or apparent path of the Sun). The 20,940 year period denotes the perihelion cycle, and represents the combined effects of the precession of Earth’s rotational axis and its eccentric orbit. The perihelion cycle is one of the Milankovitch cycles, all of which affect the tidal potential on millennial time scales.

2.4. Observation of Earth’s slowing rotation and the Moon’s orbital acceleration

Observations and written records of lunar occultations, and solar eclipses led to the initial hypotheses that the lunar orbit was experiencing a secular acceleration. Following Newton’s discoveries, Edmund Halley (the namesake of Halley’s Comet) published noted discrepancies between the longitudes of then recent solar eclipses with ancient solar eclipses. This shift in longitudes led Halley to conclude that the orbit of the Moon must be accelerating. Unfortunately, Halley was never able to quantify the orbital acceleration, nor was he able to produce a physical mechanism explaining such orbital changes (Stephenson, 1978). Work on ancient astronomical observations continued, as these were the only observational data available. Stephenson (1978, 1997) details the history of these developments. Interestingly, Stephenson was able to estimate the lunar recession rate at 4.4 cm/yr by using purely astronomical observations (some ancient). This number is close to the figure of 3.82 cm/yr obtained by lunar laser ranging (Dickey et al., 1994). The establishment of the current rate of lunar recession is critical to the work of theorists and others wishing to benchmark their hypotheses.

2.5. Tidal friction

In 1754, philosopher Immanuel Kant made a theoretical claim on the subject that, while largely ignored by his contemporaries, would later claim its place as an important conceptual advance in the field. Kant claimed that the ocean tides, which were by then known to be raised by the Moon and the Sun (Newton’s *Principia* outlining the law of gravity was published in 1687), caused a retarding force that slowed the Earth’s rotation as the Earth spun through the tidal bulges (Kant, 1754). Kant, like Halley, was unable to substantiate his claims through sufficient quantitative analysis and his claims were largely dismissed by the scientific community. Nonetheless, Kant’s ideas were resurrected in the mid and late nineteenth century by the likes of J.R. Mayer, Lord Kelvin (W. Thomson), and G.H. Darwin (the son of Charles Darwin). These researchers were able to argue with a more mathematical treatment that the tides induced a torque in the Earth’s rotation that resulted in energy and angular momentum transfer from the rotating Earth to the lunar orbit. Thus, the decelerations of the Earth’s rotation and the Moon’s orbit were linked in theory. Incidentally, these advances followed the work of Laplace, who himself, explaining some of the lunar acceleration by purely conservative celestial mechanics, balked at Kant’s idea.

Despite the advances in understanding tidal theory, questions lingered into the 20th century concerning the specifics of the Earth–Moon system and its evolution. Munk and MacDonald (1960) hypothesized that the tidal bulge of the solid Earth was carried forward by Earth’s rotation, resulting in some degree of energy
dissipation and a tidal bulge delay angle whereby the tidal bulges do not lie directly on the axis connecting the respective centers of mass of the Earth and Moon (Fig. 5). This was later confirmed by perturbations in satellite orbits (see discussion in Wahr, 1988). If one re-imagines the equilibrium model for an Earth covered in water, it is not hard to envision a somewhat analogous situation occurring for oceanic bulges, and the ideas of Kant are brought to mind; of course, the equilibrium case is not realized.

The dissipation associated with oceanic waters and its innate heterogeneity required further analyses. Exactly how and where was this energy flux of barotropic tides occurring? This question posed a serious challenge to geoscientists. Lambeck summarized the situation, stating that the “nature of the dissipation mechanism, however, remains uncertain” (Lambeck, 1978). Munk and MacDonald proposed three possible methods of explaining energy transfer in the oceanic setting. Method 1 states that tidal deformation of the ocean surface results in energy flow into the deep ocean. Method 2 states that bottom friction between tidal currents and shallow shelf areas results in energy transfer (dissipation). Method 3 states that tidal currents cause energy transfer from the deep ocean to shallow shelf areas. These methods are summarized by Suendermann and Brosche (1978) and Lambeck (1980), who provide the results of energy transfer calculations (Table 1 after Lambeck, 1980).

Researchers soon employed dissipative models that were showing the effect of ocean tides on the Earth’s rotation (Brosche and Suendermann, 1972; Hendershott, 1972). Zahel, following Hendershott (1972), modeled the M2-tide from basic tidal equations and included the effects of tidal loading on the solid Earth (and resultant solid Earth deformations) and ocean self-attraction (Zahel, 1978). Suendermann and Brosche (1978) consider these effects, built a tidal friction model on the basis of Method 1 discussed by Munk and MacDonald and hydrodynamic equations which described the evolution of fluid movement and energy. Employing a simple two-depth bathymetric model that could be used to approximate Permian bathymetry, the authors obtained a dissipative energy value of $-E_{\text{rot}}=4.5 \times 10^{12}$ J/s for the modern ocean. This was obtained without the advanced considerations of solid Earth deformations and full suite of tidal constituents, but is a reasonably close to values produced via more robust models. Performing these calculations for the Late Permian (250–260 m.y. BP), when the super-continent of Pangaea was present, the authors arrive at $-E_{\text{rot}}=3.0 \times 10^{12}$ J/s. As Pangaea was accreting in the Early Permian (299–270 m.y. BP), the distributions of landmass and oceans were slightly different. The authors compute $-E_{\text{rot}}=1.4 \times 10^{12}$ J/s for this period. Importantly, the differences in energy dissipation imply that moderate differences in the shapes of the oceans can dramatically impact the average tidal torque acting on those oceans. Both the Early and Late Permian values are much smaller than the modern values. This implies a much smaller transfer of angular momentum at times in the geologic past. These implications, taken together, suggest a complex history of lunar acceleration and change in length of day. The high rate of dissipation observed currently by lunar laser ranging may be anomalous. Discussions of continental configurations and tidal friction are also provided in Krohn and Suendermann (1982), Thiede (1982), and Kagan (1997).

At the modern rate of dissipation, assuming no decreases in the geologic past, it is true that the Moon would have reached the Roche limit (the minimum distance of the Moon from Earth whereby the Moon is not torn apart by tidal forces) around 2 Ga (Scrutton and Hipkin, 1973). Dated lunar basalts along with paleontological and sedimentological data (discussed in Section 3) strongly contradict this notion. A compilation of the history of lunar recession and the variations thereof was needed (Brosche, 1984).

### 2.6. Earth’s moment of inertia and angular momentum

Early work on surmising Earth’s past moment of inertia was performed using Kepler’s laws and coral data from the Devonian (Runcorn, 1964). The ratio of orbital angular momentum of the Moon to the Earth is derived. From this, the relation

$$B(L_o-L)=(N_o-N)$$

is obtained, where $B$ is the ratio of solar to lunar tidal dissipation, $L$ is the Moon’s orbital angular momentum, $N$ is the Earth’s orbital angular momentum, and a subscript denotes present values while no subscript denotes past values. The ratio of Earth’s orbital angular momentum to the Moon’s is quite large ($N_o/L_o\approx 10^6$). Runcorn, from this, and the relation above, surmises that $N_o/N_m=1$. This implies little change in the length of the year (in consistent temporal units) over time. With these equations, the ratio of Earth’s past to present moment of inertia as it spins on its axis can be computed. If the length of the year (in absolute time) has not changed, $I=I_o(0.999 \pm 0.003)$ for mean $B=1/3.7$, and $I=I_o(0.994 \pm 0.002)$ for mean $B=1/5.5$. Brosche and Wunsch (1990) have placed the value of $B$ as between 1/4.7 and 1/5.1; thus, from two

<table>
<thead>
<tr>
<th>Researcher</th>
<th>Method</th>
<th>$\frac{dE}{dt}$ (10^{12} J/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jeffrey (1920)</td>
<td>Bottom friction</td>
<td>1.1</td>
</tr>
<tr>
<td>Groves and Munk (1958)</td>
<td>Torque</td>
<td>3.2</td>
</tr>
<tr>
<td>Miller (1966)</td>
<td>Energy flux</td>
<td>1.7</td>
</tr>
<tr>
<td>Pekeris and Accad (1969)</td>
<td>Bottom friction</td>
<td>4.2*</td>
</tr>
<tr>
<td>Hendershott (1972)</td>
<td>Torque</td>
<td>3.0</td>
</tr>
<tr>
<td>Kuznetsov (1972)</td>
<td>Torque (Pekeris and Accad model)</td>
<td>3.3*</td>
</tr>
<tr>
<td>Zahel (1978)</td>
<td>Bottom friction</td>
<td>3.8</td>
</tr>
</tbody>
</table>
of Kepler’s laws and observational data, it appears that the length of the year and Earth’s moment of inertia have experienced little change since at least the Devonian.

Geophysical evidence suggests the Earth has undergone little expansion/contraction since the Precambrian, supporting the notion that there was not a terrestrial mechanism driving changes in the moment of inertia (discussed in Williams, 2000). The assumption that year length is nearly fixed is dependent on little change in the value of the universal gravitational constant \( G \) (Runcorn, 1964). Changes in \( G \) could cause significant changes in moment of inertia. There has been some debate as to the validity of the assumption of a nearly uniform \( G \) (Mazumder and Arima, 2005). In some hypotheses and theories it is employed as a variable (e.g. the large numbers hypothesis, superstring theory, and some theories of gravitational evolution) (European Space Agency, 2000). This debate has been aided by the ongoing difficulties in measuring its current value to high precision. However, lunar laser ranging and other data suggest only very minute changes in the orbital radii of several planets and satellites (Williams, 2000). A current estimate from helioseismology places the rate of change of \( G \) at \( \frac{dG}{dt}/G = -1.6 \times 10^{-12} \text{yr}^{-1} \) (Guenterth et al., 1998). This yields a value of \( G \) at 620 Ma within approximately 0.1% of the current value.

Calculating the Earth’s moment of inertia as being near constant establishes that significant changes in the length of day are due to tidal dissipation, not other effects related to changes in moment of inertia. The rate of change of the length of day does appear to vary slightly through time on small scales (e.g. days and weeks) (Lambeck, 1980; Stacy and Davis, 2008). These are very high order effects where small changes in Earth’s moment of inertia could account for some of the observed variations in Earth’s rotation.

Along with Earth’s moment of inertia, the total angular momentum of the Earth–Moon system is assumed, via the principle of conservation of angular momentum, to be very nearly constant through geologic time, with the lunar orbit gaining momentum lost by Earth’s rotation due to tidal friction. Computations reveal that about 86.8% of the Earth–Moon angular momentum comes from the orbital angular momentum of the Moon. About 12.1% is derived from the daily rotation of the Earth, and 1.1% from the rotation of the Earth around the center of mass of the Earth–Moon system (Lliboutry, 2000).

2.7. Tidal theory and the evolution of the Moon

The flux of orbital and rotational quantities in the Earth–Moon–Sun system was being calculated from fundamental principles and assumptions, as well as some paleontological data. However, there needed to be further tests of the assumptions and the data. The question of the timing of the Moon’s formation also persisted. By the late 1970s, there was convincing geologic evidence (discussed in the Geologic tidal data section) that the Moon was far older than the 2000million year formation date many calculated. The ideas and questions provided by previous studies were soon utilized in the creation of numerical models that aimed to study the effects of tidal dissipation on the Earth–Moon system.

Hansen (1982) created a model whereby dissipation was taken to occur by linear bottom friction. Two continents were placed on the rigid sphere; a single continent at the North pole and a single continent at the equator. The model then computed, via Laplace’s tidal equations, the tidal amplitudes. The angular momentum of the Earth–Moon system was computed using only the revolution of the Earth–Moon system around the center of mass. Laplace’s tidal equations (LTE’s) needed to be solved to provide the parameters for the energy computations at various stages and to integrate the orbital equations backward in time. A two-depth model akin to that employed by Suendermann and Brosche was used. In this model, dissipation results from bottom stress, and most tidal dissipation in the model occurs in shallow seas. The computations suggested that the Earth–Moon distance at 4.5 Ga was never less than 38 to 53 Earth radii (depending on the continental configuration and frictional coefficients used). In addition, the results of the simulation suggested that dissipation was halved as the length of the day approached 20 h from 24 h and that there is currently a resonance between the M2-tide and the oceanic normal mode (eigen-frequency). These results appear to be in harmony with the geologic evidence, and suggest lunar formation occurred early in Earth’s history. From these results, and those of Lambeck, it seems that the assumption of conservation of Earth–Moon angular momentum is, to higher-order, correct.

Similar investigations using models that explored the effects of ocean continent distribution on Earth–Moon evolution found that continental distribution was, indeed, influential in tidal dissipation processes (Abe and Ooe, 2001). Resultant calculations of length of day differed according to continent placement after 1.5 billion years BP; however, it appears that Earth–Moon evolution was only slightly affected by different continental distributions prior to this time. This may suggest that tidal frequency values before 1.5 Ga deviated far from the eigen-frequency of the tidal response of the oceans (i.e. no resonances between tides and ocean normal modes). These results, and those obtained by Suendermann and Brosche, 1978 and Hansen (1982), seem to indicate a nonlinear, variable rate of dissipation throughout Earth’s history. It has been postulated that the oceans may enter and exit periods of resonance with the M2-tide in geologically short time intervals (e.g. ~5 million years) (Kagan, 1997).

3. Geologic tidal data

3.1. The geologic record and tides

The notion that the rotation of the Earth and the orbit of the Moon may be changing was unknown until astronomical evidence indicated such phenomena. Theoretical work on tides and tidal dissipation advanced in concert with the development of increasingly robust mathematical and computational tools, and an increasingly lucid description of tidal processes in the modern regime has been constructed. Probing the past evolution of these processes as related to long-term variations of the boundary conditions on Earth has proven problematic, largely because of the paucity of evidence that has been gleaned from the geologic record. This issue began to be addressed in the 1960s with the analysis of growth lines on ancient corals and bivalves (e.g. Wells, 1963; Scrutton, 1965; Berry and Barker, 1968; Mazzullo, 1971; Kahn and Pompea, 1978). The recognition of what appeared to be daily and/ or monthly growth rings on these fossils suggested that researchers could estimate the number of days in the year and/or the number of days in the lunar month as far back as the Ordovician. Researchers used these data in calculations to estimate past to present ratios of Earth–Moon angular momentum and Earth’s moment of inertia to be near unity. However, the limitations of the paleontological data soon became apparent. The accuracy of the fossil record in yielding an accurate estimate of the number of days per year or month was problematic. It remained uncertain whether the growth bands represented stimuli from sunlight and represented a solar day, or if they represented changes in response to water height, and represented a lunar day, or, whether the growth bands represented some other unknown periodicity or process related to non-environmental factors. Evidence of the inaccuracies of the fossil record is shown by tidal energy dissipation calculations and is summarized by Williams (2000).

The eventual recognition of neap-spring cycles in certain rocks, called tidal rhythms, offered researchers unprecedented accuracy in surmising ancient lunar periodicities. It is generally accepted that when tidal cyclicities are preserved in vertically accreted mm-scale laminae, the term ‘tidal rhythmite’ is to be applied (Fig. 6) (Williams, 1989). When tidal cyclicities are preserved as laterally accreted
foresets, the term ‘tidal bundle’ is used (Fig. 7). Although foreset laminae and sandy bedform foresets are deposited via different mechanisms, the underlying energy forcing these processes is provided by the tides.

3.2. Analysis of modern tidally influenced systems

The studies of modern tidal settings served as a precursor to the studies of the stratigraphic record of tidal environments. These early developments are summarized by Klein (1976) and are outlined below. A thorough compilation of more recent work in the intertidal zone is presented in the volume of Black et al. (1998). The first of these modern studies were undertaken in the 1920s at the Senckenberg Marine Laboratories along the North Sea in Germany. Much of this early work, particularly that of Rudolph Richter, focused on the biological and paleontological aspects of the intertidal regime. More rigorous sedimentological studies were performed by Walter Haentzschel in the 1930s. In fact, the translation of Haentzschel’s 1939 paper, “Tidal Flat Deposits (Wattenschlick),” is one of the first tidal flat sedimentation studies published in English (Haentzschel, 1976; Klein, 1976). The primary goal of this work was to identify and understand the processes associated with the deposition of tidalites (sediments deposited under the action of tidal currents in intertidal and subtidal zones, but not necessarily preserving tidal periods). The most prevalent tidal bedding feature on most mesotidal and macrotidal flats are tidal laminations, which were ascribed to tidal origin as early as 1841 by Forchhammer. Haentzschel, progressing these notions, proposed that flood tides, loaded with suspended matter and sediments of varying grain size, were responsible for deposition of the sand lenses as velocity decreased below a threshold value. At slack water, or the turn of the tide, the fine-grained mud then settled out. This qualitative model would form the basis of subsequent studies seeking to understand deposition of individual beds under direct tidal action.

Qualitative explorations of the environment and deposition were marginally successful in their use in interpreting the rock record. Early studies of the Lower Devonian Hunsruck shales of Germany lead many to believe that, due to their very fine-grained texture, these rocks were of deep-sea origin. In 1931, however, Richter noted similarities between these shales and modern tidal flat deposits and the occurrence of flow structures indicative of subaerial exposure. This claim was met with skepticism, as it was reasoned that tidal flat sediments and associated rocks are probably uncommon, as the intertidal zone is quite small and susceptible to reworking. These problems underscored the need for more rigorous studies and precise collection of data, and would remain at the fore in the years to come.

World War II saw the interruption of most significant tidal flat studies, as German and English scientists were the primary tidal flat researchers of the time. Dutch researchers working in the Wadden Sea carried on their predecessors’ work (van Straaten and Kuenen, 1957; Postma, 1967, 1976). The working model for tidal flat deposition was one where mud was deposited at slack water with very low wave

Fig. 6. Foreset laminae from the Hindostan Whetstone Beds (Pennsylvanian) of Indiana, USA exhibiting neap-spring cyclicity. The accompanying graph displays measurements of individual sandy laminae thicknesses. From Kvale et al. (1999).
velocity and shallow depth. One of the resulting implications of this model would be the accumulation of mud on the high tidal flats, where flood tides extended to their maximum landward position and possessed the prerequisite low wave velocity and height. This mud accumulation was generally observed; however, there were intricacies present in the distributions of grain size and suspended sediment that demonstrated the need for more precise ideas. Postma attempted to explain the existence of mud on the high tidal flats in a more rigorous manner. The idea of “settling lag” was proposed, whereby particles, rather than settling out immediately once the threshold velocity is reached, are transported more landward due to the forward inertia of the wave entraining the particles (Postma, 1954). An additional mechanism of intertidal zone dynamics was soon introduced that explained the pervasiveness of mud throughout most of the Wadden Sea tidal flats (van Straaten and Kuenen, 1957). The idea behind this mechanism, named “scour lag,” was that erosional velocities exceed depositional velocities. This had been suggested in previous findings (Hjulström, 1939). Settlement and scour lags have been observed in other localities, such as in the extreme intertidal environment of the Bay of Fundy, in Canada (Klein, 1963). Further studies revealed that the asymmetry between the flood and ebb tides, when the flood phase was dominant, could work in unison with the scour lag effect to favor mud accumulation in the landward direction (Postma, 1967, 1976; Groen, 1976). Utilizing a simple mathematical treatment, Groen was able to reproduce the time variations of equilibrium and suspended loads by taking the change in suspended sediments at any time as proportional to the difference between actual suspended load and equilibrium load. The author reported a nearly 38% difference in displacement of suspended sediments between high and low tides.

A rigorous analysis of the bedding types observed in the intertidal and subtidal environments was also being conducted. Reineck and Wunderlich (1968) were among the first to systematically categorize differences observed in the geometries and compositions of beddings from paralic environments. While flaser, lenticular, and wavy (sometimes called ripple) beddings were well known, few had attempted a meaningful classification scheme. The distinctions between these beddings (actually, laminations when the individual units are less than 1 cm thick) are important, as they permit study and classification of the origin of the bedding types. For instance, it was long recognized that ripple-bedding was formed from alternating currents and oscillatory flow related to tidal currents. However, the question of differing modes of mud deposition in the beddings proved to be more elusive. The exact effects of the tides and underlying sand beds on mud sedimentation were not known. Early studies did make interesting suppositions concerning this matter. Haenztschel’s model for flaser bedding proved generally correct; during rising and falling tides, when currents are active, the sand is transported and deposited, while during slack water, the mud is deposited on the sand ripples (in the troughs, and, perhaps, on the crests). When current activity resumes, sand deposition may resume or the mud may begin to erode, leaving only some mud in the ripple troughs. Reineck proposed that lenticular bedding, showing only incomplete sand ripples (sand lenses), represented the migration of ripples into a muddy basal layer. New mud layers are deposited where the troughs of the ripples were (before migration), and contact the muddy basal layer. This gives the sand ripples the appearance of sand lenses.

Related to flaser, wavy, and lenticular beddings, was “rhythmically laminated bedding.” This sort of bedding had been recognized as early as 1929, by Richter. It was postulated that the sand layers were “remnants of very flat-crested ripples that posses[ed] nearly straight crests” and that the fine rhythmically laminated bedding originated in fast-flowing waters that were high in suspended sediment concentrations (Reineck, 1967). It was thought that slower current velocities would be required for the formation of the thicker layers comprising coarse rhythmically laminated bedding (at the cm scale). For either fine or coarse beddings, the relation to tides was not fully articulated. It was proposed that, for both fine and coarse beddings, every tide could result in the deposition of many laminae. However, previous authors held the contention that a single sand lamina was deposited...
during flood tide, and a single mud lamina was deposited during ebb tide. Reineck, claiming that a single tidal cycle did not necessarily result in many laminae, stated that the sand layers were formed during periods of current activity, and the mud layers were deposited during slack water. 

Tube and flume experiments were performed testing hypotheses regarding the origins of flaser, lenticular, and wavy beddings (Terwindt and Breusers, 1972). It was found that thicker mud layers have smaller initial consolidation rates and lower critical velocities, resulting in a higher probability that erosion will occur. The authors also observed that higher sand content in the mud led to more rapid consolidation and higher critical velocities up to a sand content of 40% (more sand yielded decreasing critical velocity). Drainage from under the mud layer also increased initial consolidation rates. In the case of flaser bedding, with its thin mud layers, the data suggested that wave velocities do not greatly exceed the critical velocity, and mud layers may be removed from crests but generally not troughs, as the wave velocities are generally lower in the troughs. The authors claimed that wavy bedding, where mud is often preserved on the ripples, is a result of velocities just below the critical velocity. Thus, small deviations around the critical velocity in the tidal current produce either flaser or wavy bedding. These views are in general agreement with the qualitative ideas proposed by Reineck.

The depositional dynamics of the fine-grained muddy sediments proved more difficult to surmise than the accompanying coarser silts and sands. McCave (1970) studied the thickness of mud layers in tidal deposits and adopted a “quasi-continuous” model of deposition, whereby fine-grained sediments are deposited not only at slack water, but also during certain periods of flood and ebb tides. In addition, he employed a viscous flow model, after Einstein (1950), that assumed a viscous sublayer that accepts sediments by settling, but rarely ejects particles back into the flow. Deposition then occurs from settling at a reduced but quasi-continuous rate from the viscous sublayer. McCave, based on numerical modeling, goes on to suggest that the alternating sand and mud deposits, such as those seen in flaser bedding can be due to periodic storm activity, and that such bedding may not be tidally induced, as the suspended sediment concentrations appeared too low to yield the mud layer thicknesses observed in some deposits. Terwindt and Breusers, on the basis of the experimentally observed rates of deposition (from the particle falling velocity) and initial consolidation rates, also stated that the thicknesses of the mud layers were too great to be deposited during a single slack water. Simultaneously, there was a debate over the effects of disturbance (sediment ejection from the viscous sublayer). It was argued that many studies employed only laboratory results from water flow in pipes (Terwindt and Breusers, 1972). The Reynolds numbers (determines whether a flow is laminar or turbulent) in these experiments indicated complete disturbance at values that were known to be less than those found in actual waterways without complete disturbance. This is not to say, however, that quasi-continuous mud deposition is invalid, as mud layers in tidal rhytmihes have been observed in systems that experience extremely brief slack water periods and can be attributed to some flood or ebb phase deposition. Thus, despite advances, there was no consensus as to the exact nature, timing, and relation to tidal cycles of many fine-grained deposits. This was particularly true for muds found in wavy and lenticular beddings. Definitive data from actual tidal environments were needed.

3.3. Quaternary tidal bundles/rhythmites

The 1980s saw an end to much of the prior speculation and uncertainty regarding the nature and form of tidal deposits. The production of direct empirical data, particularly tidal deposits that exhibited neap-spring cycles, provided a timeframe for deposition in the natural setting that could be related to changing energy regimes throughout the tidal cycle. Visser (1980) published results of a study from the North Sea of Holland in which neap-spring cycles were observed in Holocene deposits. This provided convincing evidence that a single sand or mud lamina could be deposited during a single tide event. The study area formed part of a tidal inlet that, until 1867, was part of an estuary. The deposits were dated to the seventeenth or eighteenth century, based on hydrographic map data and the occurrence of a particular mollusc (Mya arenaria). The facies consisted of sandy foresets enclosed by thin mud laminae (Fig. 7). The thicknesses of the sandy foresets varied periodically, with a period roughly equal to that of a neap-spring cycle. The estuarine environment of the time indicated that the deposits were subtidal. Preservation of the sedimentary features was attributed to deposition in the bottom of a channel. Visser notes the presence of unidirectional bedforms in the deposits. Unidirectional bedforms in other tidal deposits were previously noted (Raa and Boersma, 1971), and, according to Terwindt (1971), indicate a tidal current asymmetry. Visser goes on to provide a qualitative model to explain the structures observed (Fig. 8). The general sequence of laterally prograding sandy foresets (migration of the sand wave) accompanied by thin silt layers was also seen in prior studies, such as the Cretaceous Polkestone Beds of Britain, although few specifics were provided as to the formation of such features (Allen and Narayan, 1964; Nio, 1976). Evidence indicates that the process begins with deposition of sand on the lee side of a ripple during the dominant current stage (in this case the ebb tide) (Allen, 1982). The subsequent slack water results in mud deposition over the several centimeter sand layer. During the subordinate current stage some mud and sand laminae/beds are eroded near the top of the lee side, but sand deposition does occur between the topset and bottomset (but less than during the dominant current stage). The following slack water results in deposition of a thin mud lamina.

Since the initial recognition of tidal bundles in recent to sub-recent deposits, other researchers have identified neap-spring cycles in Holocene and Late Pleistocene deposits from various localities around the world. Modern tidal flats have been particularly demonstrative of high resolution tidal deposition. In particular, macrotidal flats from regimes experiencing some of the highest tidal ranges on the planet have revealed trends in deposition and depositional setting. These environments generally possess vertically stacked planar heterolithic laminae (cyclic tidal rhytmhites) that are tidal in origin (Archer and Johnson, 1997). Tidal flat rhytmhites have been observed in the macrotidal regime include: Bay of Fundy in Canada (Dalrymple and Makino, 1989; Dalrymple et al., 1991), Turnagain Arm in Alaska (Atwater et al., 2001; Greb and Archer, 2007), the Mont-Saint-Michel bay in France (Tessier, 1993), the Severn Estuary in Britain (Allen and Duffy, 1998), the Seine Estuary (Deloffre et al., 2005, 2006, 2007), tidal flats on the western coast of Korea (Park and Choi, 1998; Choi and Park, 2000), and the Changjiang Estuary in China (Fan and Li, 2002). Rhytmhite deposits have also been reported from a submerged marsh (Romney Marsh) in the United Kingdom, where peat compaction and marine transgression have facilitated the creation of accommodation space (Stupple, 2002; Long and Waller, 2006). Rhytmhite deposits that have been reported from mesotidal flats include: tidal bundles similar those observed by Visser (1980) from intertidal shoal deposits in Holland (Boersma and Terwindt, 1981) and, also in Holland, tidal channel fill deposits with sandy foresets possessing a mean periodicity of 27 laminae (Roep, 1991). In Britain, tidal rhytmhites have been reported from a microtidal estuary in West Wales (Shi, 1991).

Moving headward into the fluvial–tidal transition, heterolithic strata that may preserve tidal periodicities can be found along the bends of the fluvial channel(s); these deposits often dip toward the channel and are known as inclined heterolithic strata (IHS) (Thomas et al., 1987). Sedimentary morphodynamics are reflective of the mutually evasive fluvial and tidal currents and facies from the fluvial–tidal transition will exhibit varying degrees of fluvial and tidal
influences (Van den Berg et al., 2007). Few studies have documented tidal cyclicity in fluvial–tidal deposits, although Jaeger and Nittrouer (1999) demonstrated that sandy bedforms could be formed and occasionally preserved during spring tides at the mouth of the Amazon river, while during neap tides only mud laminations were deposited. A thorough overview of the deposits and processes observed in modern fluvial–tidal regimes is given by Dalrymple and Choi (2007).

Glacier-fed deltas in fjords may produce neap-spring laminae (Smith et al., 1990; Cowan et al., 1999). Smith et al. (1990) hypothesized that during neap tides, when the tidal range is smallest, the intertidal mudflats and channels remain subaqueous. As a result, most sediments are confined to the intertidal zone, and only a minimum of sediments (primarily fine-grained) remain in the basin. During spring tides, however, when the tidal range is largest, the intertidal area may be subaerially exposed during low tide. As a result, sediments can be transported to the basin seaward of the intertidal zone and sand deposition results. During high tides much of this sediment will be reintroduced to the intertidal area, and the basin will experience some fine-grained sediment deposition that will also be subsequently eroded by the next flood tide during spring cycles. These processes produce vertical sequences in the subtidal basin that exhibit sand–mud couplets representing spring tides, and fine-grained laminae that represent neap tides. Larger-scale rhythmites from fjord deposits in Norway dating to 8–9 kyrs have also been analyzed, with a proposed sedimentation mechanism similar to that describe by Smith et al. (Eilertsen et al., 2005). The study of well-known modern settings and their resultant tidalites may foster recognition of numerous variables (depositional environment, basin geometry, etc) in the ancient record.

3.4. Ancient rhythmite depositional environments and processes

The definitive recognition of tidal deposits in the stratigraphic record has proven elusive, and has been summarized previously (Raaf and Boersma, 1971). Such was the situation, that they added, “At the present state of knowledge a reliable determination of the tidal sub-environment (e.g. nearshore, offshore, intertidal, and subtidal) seems to be virtually impossible for ancient clastic deposits, except for a few cases” (Raaf and Boersma, 1971). However, that same year, Klein published findings that sub-environments and, subsequently, paleotidal ranges could be surmised (Klein, 1971). He claimed that tidalites may be recognized by a series of features that arise from 10 phases of tidal sediment transport. Individual features may provide evidence of tidal deposition, but may also be misleading; many features seen in tidalites are also observed in fluvial, or Aeolian environments. In fact, even some small-scale structures, such as flaser, wavy, and lenticular
bedding can occur in non-tidal environments (Kvale and Archer, 1990). The important concept provided is that it is the combination of features observed that distinguishes tidal from non-tidal deposits (Klein, 1971; Terwindt, 1988).

Work continued in identifying tidal deposits and cycles in the rock record, as examples were collected from various periods throughout the world. Unfortunately, interpretation of depositional environments has generally remained elusive, as modern and ancient analogs are not always known. Rhythmites from the ancient record include the Archean rhythmites of South Africa (Eriksson and Simpson, 2000), the Paleoproterozoic of India (Mazumder, 2004), the Precambrian of Wisconsin (Davis, 2006), the late Precambrian of Scotland (Kessler and Gollop, 1988), the late Precambrian of Australia (Williams, 1989), and the late Precambrian of Utah (Chan et al., 1994). There are numerous examples from the Carboniferous of the interior of the United States (Greб and Chesnut, 1992; Martino and Sanderson, 1993; Kvale et al., 1994, 1995; Greб and Archer, 1995; Kvale and Mastalerz, 1998; Kvale et al., 1999). Tertiary deposits have been found in the Miocene of France (Tessier and Gigot, 1989), the Miocene of Peru (Hovikoski et al., 2005), the Eocene of Belgium (Houthuys and Gullentops, 1988), Spain (Santisteban and Taberner, 1988), and delta-front deposits from Oregon (Leithold et al., 1989). Evidence for non-siliciclastic tidalites has even being compiled by recognition of fine cyclic laminae in carbonate tidal deposits from Middle Jurassic rocks in Britain (Ashton, 1981) and rhythmites in Carboniferous limestones (Brown et al., 1990).

As more rhythmites were uncovered and studied, comparative analyses could be made. Of particular interest were the various beddings and depositional environments observed in these sections. Neap-spring cycles were recognized in bedding scales that ranged from meter-scale mega cross-bedding (Kessler and Gollop, 1988) to mm-scale laminations (Williams, 1989). In addition to the differences in bedding scales, bedding types and depositional environments were marked by diversity. While the depositional environments discussed by Visser and Allen were interpreted as subtidal, research of vertical tidalites finds both the intertidal and subtidal regimes as viable depositional environments of vertical tidal rhythmites (Roep, 1991; Atwater et al., 2001; Greб and Archer, 2007). Below, several of the seminal studies are discussed because they outline the advantages and difficulties that are often encountered when working with tidal rhythmite/bundle records.

The oldest observed tidal deposits displaying what may be tidal cyclicity were found in rocks dating to 3.3 Ga, and were recognized with the use of features reported by Klein and others (Eriksson, 1977). The Archean Moodies Group from South Africa contained four distinct tidally influenced facies. Observed was a sandstone–shale facies that exhibited flaser, lenticular, and wavy beddings. It was postulated that this rhythmically bedded shale–sandstone formed under low current action in an environment analogous to estuarine tidal flats in the Netherlands. A similar study followed, where rocks from the Witwatersrand Supergroup in South Africa dated from 2.5 to 2.8 Ga were also shown to exhibit tidal characteristics (Eriksson et al., 1981).

Precambrian mm-scale, vertically accreted rhythmites from the Elatina Formation of Australia have been interpreted as originating in a distal ebb tidal delta setting (Williams, 1989, 1997, 2000). It is argued that these were regions suited for tidalite preservation because of associated low wave energies and “rapid deepening beyond the terminal lobe of the ebb tidal delta.” Assuming a uniformitarian model, such environments would have been relatively common in the Precambrian, as they are today. Williams reported that the Elatina Formation displayed similarities in form and pattern to certain modern data. The Reynella Siltstone Member of the Elatina Formation displayed herringbone cross-bedding, corresponding to alternating flood and ebb tidal currents, which is, of course, observed in modern settings possessing alternating currents. In addition, the Reynella Siltstone was interpreted as displaying a diurnal inequality for the semidiurnal tides. Despite similar deposits being ascribed to a similar environment of deposition (Miller and Eriksson, 1997), modern rhythmites from such a setting have not been reported. Dalymply and Choi (2007) summarize: “There are very few detailed descriptions of the delta-front and prodeltaic deposits of strongly tide-influenced deltas” (p.164). Interestingly, somewhat similar modern, deep-water deposits from a fjord setting have been reported (Cowan et al., 1998). The sampled laminae exhibited rhythmic thickening and thinning. This may be the feature that is most indicative of tidal deposition (sub-environment notwithstanding), as the periodicity is close to that of fortnightly neap-spring cycles.

Evidence of a freshwater or low-salinity depositional environment from the Carboniferous rhythmites of Indiana has been analyzed (Kvale and Mastalerz, 1998). Neap-spring cycles in finely laminated deposits akin to those of Roep and Tessier, but of Pennsylvanian age, are noted in the Mansfield Formation (Kvale et al., 1989) and the overlying Brazil Formation (Kvale and Archer, 1990). The whetstone beds of the Mansfield Formation are composed of planar, horizontal foreset laminae composed of upward fining silt and an overlying clay drape. Successive laminae generally exhibit a thick–thin pairing suggestive of diurnal inequality. Laminae thicknesses exhibit a regular pattern of thickening and thinning with a period of around 30 laminae, suggestive of neap-spring cyclicity. The Brazil Formation possesses several facies that have been interpreted as tidally influenced. The lowest of these is parallel-laminated mudstone, with laminae fining upward from siltstone to claystone. Spectral analysis of laminae thicknesses revealed a dominant period of 12.5 laminae per cycle. The second facies consists of parallel-laminated sandstone and mudstone couplets. These couplets exhibit two variations of mud laminae; a claystone–rich mud layer that is 1–2 mm thick with a sharp upper and gradational lower contact, and a siltstone-rich layer that is 1–8 mm thick with sharp upper and lower contacts. The claystone-rich laminae are coupled with sandstone laminae that may reach 3 mm in thickness, while the siltstone-rich laminae are coupled with sandstone layers that reach only 1.5 mm in thickness. No sedimentological postulate for these variations is provided, however, spectral analysis revealed a periodicity of 14.3 laminae per cycle.

In both formations, the tidal rhythmites occur between two low-sulfur coal beds. Low-sulfur coals typically indicate the roof rock is of non-marine or a low-salinity marine origin. That tidalite genesis could occur in such settings is plausible. Tides are known to propagate hundreds of km upstream in certain fluvial systems, such as the Amazon and Hudson Rivers (Archer, 2005). Conversely, freshwater river plumes may propagate into the sea for tens of km or more (e.g. Amazon River). Kvale et al. note the lack of marine fossil flora and fauna, and the dominance of “woody-like terrestrial material” that suggests a non-marine setting. Geochemical evidence of high carbon to inorganic sulfur ratios also indicates a low-salinity setting. The possibility of fresh water tidalites adds complexity to studies wishing to employ tidal rhythmites for paleographic reconstructions. Kvale states that, “Both inland and coastal examples are not generally recognized from the rock record ...” (Kvale and Mastalerz, 1998, p. 104). It is, therefore, possible that freshwater tidalites, if they exist, may be misinterpreted as coastal deposits. The interpretation of the periodicities observed in these sediments could yield clues as to whether tidal influence was present (be it a saline or freshwater environment), while the recognition of salinity in the environment may be ascertained via paleontological analysis (Buatois et al., 1997). To date, no modern rhythmites have been found in the headward portions of the fluvial–tidal regime.

The Folkstone Beds of England displayed evidence of ancient tidal deposition, and were used in early studies of depositional processes (Allen and Narayan, 1964). These Lower Cretaceous deposits consisted of mega-scale cross-bedding of graded foresets sometimes accompanied by thin silt layers and exhibited features similar to those observed by Visser. Where the silt layers are present, the foresets
meet the base of the unit at a very low angle and are graded from fine to coarse as one moves upward and perpendicular to the silt layer bounding surface. In addition, small-scale cross-stratified ripples are observed within the lowest part of the foresets (the bottomsets). Allen and Narayan had previously resolved to surmise the sedimentation mechanisms of the system by direct experiments. Replication of the bedding observed in the Folkstone Beds was achieved via the use of a flume and deflector plate, which resulted in the creation of a large medium-grained sand ripple. When water velocities in the flume were increased, sand transport commenced and resulted in erosion of the stoss side of the ripple. This eroded sand was then transported up and over the crest of the ripple, where it was deposited in small avalanches on the lee side of the ripple. When velocities decreased sufficiently, clay present in the flume began to settle and form a bounding surface on the sand. When velocities were increased, this clay layer was buried under a sandy layer and remained mostly preserved. The small-scale ripples observed in the beds were also seen in the experiment. The authors attribute the formation of these to a counter current that forms on the lee side of the ripple. The primary features observed in the Folkstone Beds are present in the flume experiment. The experiment included only a unidirectional flow.

In 1981, a revision of the Folkstone Beds model was published following discovery of neap-spring cycles in the Folkstone Beds (Allen, 1981). This represented the first reported recognition of neap-spring cycles from an ancient tidal regime in the depositional record. It was postulated that the deposits were derived from a shallow marine environment, as indicated by the presence of ammonites, bivalves, sponges, driftwood and the sedimentary features previously discussed. Thickness variations in the foreset beds appeared to indicate the presence of four neap-spring cycles, some of which appeared to be incomplete, as the cycle lengths varied from 16 to 32 beds. This was interpreted as suggesting the suppression of mud deposition, perhaps owing to changes in mud concentrations, growth of wind waves on the water surface (which increases stresses on shallow bottom), storm currents, or the minimum wave velocities exceeding settling thresholds. Despite the irregularity in cycle lengths, it was believed that the sediments revealed neap-spring cycles in a semidiurnal system, as three of the four cycles ranged from 28 to 32 sandy foresets in length. This is close to the duration of the synodic half-month (14.76 days).

A further, quantitative treatment that included models of sand and mud deposition in tidal environments preserving neap-spring cycles was also provided (Allen, 1982). In this study model data was correlated with that from the Folkstone beds. The general equations for both sand and mud deposition were provided. The form of these equations is straightforward, and they describe deposition via simple assumptions. Sand transport by tidal currents over sand waves is given by

\[ J(t) = k(U(t) - U_{peak}(D))^n \]

where \( J(t) \) is the mass of dry sand transported, \( k \) is a dimensional coefficient that depends on the Reynolds number, \( U(t) \) is the mean speed of the tidal current, and \( U_{peak}(D) \) is the threshold speed of sand movement. In this equation \( n = 3 \), and this value is derived from flume data. Subsequent modelling of laminae thicknesses, whereby \( U(t) \) is approximated by changes in tidal height, has yielded good correlations to measured deposit thicknesses gathered in modern estuaries (Archer and Johnson, 1997).

In both Visser’s and Allen’s tidalite sets, and Boersma and Terwindt’s tidal deposits, unidirectional bedforms were observed due to tidal current asymmetries. These asymmetries are also known to exist from direct empirical evidence of tidal current velocities. They are likely caused by at least two processes discussed by Allen. One process is tidal wave distortion in shallow water due to interaction with the bottom. Another potential cause is a unidirectional, non-tidal current, such as that from a stream. It is interesting to note that stream currents themselves are often unsteady and may reflect regional climatic and seasonal trends. It is thus conceivable that tidalites from estuarine systems could detail such ancient trends (Kvale et al., 1994).

The recognition of the dominance of one tidal component over the other led Allen to produce a model of deposition very similar to that of Visser, in which sand waves are built laterally with sandy foresets and accompanying mud drapes as a result of unequal tidal currents. This qualitative model is in general agreement with the equations for sand and mud sedimentation. This is seen in Fig. 9, displaying sand transport predicted by the model for strongly asymmetrical tides. For the dominant tidal component (i.e. ebb or flood) there is much sand transport and, thus, deposition. Near slack water there may be mud deposition, or no transport of mud, depending on the duration and strength of this period. As the subordinate tidal component arrives, velocities increase, but only marginally. This may result in minimal sand transport and/or mud deposition. The subsequent slack water users in further mud deposition. Close analysis of the tidalite set reveals several fine structures. In particular, parting is observed where thin lenses of sand are within some mud drapes. This indicates sand or silt deposition during the period of mud deposition, and is due to changing wave conditions.

The wide range of bedding types and depositional environments observed in the rhythmites record demonstrates the variety of conditions in which tidal cycles may be formed and preserved in sedimentary strata. There seems to be a general consensus among sedimentologists regarding certain aspects of tidal rhythmite formation and preservation. Foremost among these is the idea that high sediment concentrations are required for both formation (Visser, 1980; Allen, 1981) and preservation (Tessier, 1993). This explains many of the problems of earlier models, where it was postulated that sufficient sedimentation could not occur within the time allotted by part of a tidal cycle. This also aids in explaining the preservation of rhythmites, as thicker laminae or beds experience a more rapid mud consolidation that discourages reactivation/erosion; a process observed in flume experiments (Terwindt and Breusers, 1972). In relation to this point, it is noted that the “lithologic nature” and biogenic influences of the depositional setting may also promote preservation, as some sediments experience rapid consolidation and certain biological factors may serve to fix mud laminae by production of films or debris.

3.5. Analysis of tidal rhythms

Initial studies of the periodicities encoded within tidal facies were useful in surmising neap-spring influence on deposition, but lacked precision. The most common method of analysis was the measurement of the thickness of each sand laminae. The resulting series of variable thicknesses was then visually analyzed, and neap-spring periodicities were then estimated by counting the number of laminae between troughs (or peaks) (e.g. Visser, 1980). As a result, the interpretation of specific periodicities (e.g. synodic, tropical, or anomalous) remained tenuous when studies were initially published.

Eventually, spectral estimation techniques were used in the extraction of periodicities encoded within the rhythmites. Spectral estimation techniques approximate the spectral density function, which reveals contributions to the variance of a signal from different frequency components. There are two classes of methods used to estimate spectral density: 1) the parametric methods, which calculate the spectrum from models of the data set that assume a linear series driven by noise and 2) non-parametric methods that directly transform the data (Hayes, 1996).

Perhaps the most commonly used parametric method used in stratigraphic applications is the maximum entropy method (MEM), also known as ‘Burg’s method.’ This method often yields quite good frequency resolution for short record lengths, but their use is sometimes confounded by difficulties associated with the selection
of appropriate modelling parameters, particularly the order of the model. If the selected order is too low, the spectrum is smoothed and obscures frequency content. For a selected order that is too high, spurious peaks attributable to noise content often appear. The order selection problem is non-trivial, as there is no single order selection methodology that has proven sufficient or optimal. A common starting point is to use an order equal to one third of the record length, although more sophisticated methods may be employed (often with mixed results) (Oladipo, 1988). Spectral line splitting, where two spurious frequency components bracket the actual, missing component, is known to occur in MEM spectra (Kay and Marple, 1981) and can result from improper order approximation (Barton, 1983). MEM can also exhibit peak shifting and broadening when the signal-to-noise ratio is not sufficient (Strauss, 1980).

The most commonly used non-parametric method is the periodogram, in particular the Schuster periodogram. The Schuster periodogram estimate of the power spectrum is calculated as the squared magnitude of the discrete Fourier transform (DFT) of the data divided by the record length \( N \) and sampling interval \( dt \). Periodograms are generally quite resistant to white Gaussian noise and do not suffer the peak splitting and frequency shifting of parametric methods. Additionally, the statistical significance of peak frequencies given by the periodogram can be assessed more readily (Hernandez, 1999). The drawbacks of the periodogram are that it generally yields poor frequency resolution and is susceptible to spectral leakage, which may obscure secondary peak frequencies. It has been suggested that the relative merits of the MEM and periodogram techniques promote their use in tandem as a means of cross-checking the validity of the peak frequencies while obtaining maximal frequency resolution (Gardner, 1992). The interested reader is referred to Kay and Marple (1981) for a more complete discussion of spectral estimation techniques and computational details.

While offering more precision than simple counting methods, the resulting power spectrum estimates are still subject to the imperfections of the record. Many studies presented tidalites containing neap-spring periods that are incomplete or poorly preserved. Rigorous quantitative analyses are made difficult by the imperfections presented in the record. Yang and Nio (1985) discuss two of the conditions of classical periodogram and MEM spectral estimation: 1) deposits are continuous and 2) represent sampling over an equidistant interval. A tidal record meets these conditions when deposition occurs consistently during a particular phase (flood and/or ebb) and there is no subsequent erosion of the record. In general, this condition is not met beyond a few successive tidal cycles, resulting in low frequency resolution and statistical confidence of the resulting estimates of peak frequency. When employing sub-yearly tidal rhythmites records, it is important to exercise caution when interpretations are made on the basis of peak frequency estimates. In fact, rhythmic sediments displaying lithologies similar to those observed preserving monthly periods can represent deposition over a range of temporal scales (Allen, 2004). This is not to say, however, that sub-yearly records cannot be employed to surmise peak frequencies; utilizing the MEM and periodogram techniques properly can facilitate accurate peak frequency assessment for small sample sizes (Gardner, 1992).

To test the potential efficacy of complete tidal cycle preservation in tidal rhythmites, researchers began modeling lamina deposition via predicted tidal heights and current speeds (Archer, 1991, 1995;
Archer et al., 1995; Archer and Johnson, 1997). It was demonstrated that the variations present in diurnal and semidiurnal systems were a result of various lunar/solar periodicities imprinting those systems. Employing the transport equation given by Allen (1982), which utilized empirical current threshold speeds in approximating sand layer thickness as the cube of current speed minus threshold speed, sedimentation for the tidal cycle was modeled (Archer, 1995; Archer and Johnson, 1997). Simulations using this approach revealed the role of tidal asymmetries in sediment accumulation. The role of these asymmetries is particularly important in rhythmite deposition, as the tidal curve becomes irregular near the coast. Several sedimentation patterns were observed in the model, as threshold speed was varied from low to high. For low threshold speeds, deposition in most tidal regimes was complete throughout the tidal cycle, and, in some cases, resulted in four-lamina rhythmites, whereby deposition occurred during flood and ebb tides in a semidiurnal system marked by a strong diurnal inequality. In the same low threshold simulations, some diurnal systems also exhibited complete tidal cycles and marked flood and ebb tides. Interestingly, comparison of the flood only or ebb only record of such systems reveals a strong similarity to Precambrian rhythmites observed by Williams (1989). At high threshold speeds, the tidal records became less robust, with deposition occurring only during periods of highest wave activity. Several tidal periodicities are present in the results of the simulations. The expected imprints of the synodic month in semidiurnal systems and the tropical month in diurnal systems are present, as well as the more unexpected effects of the anomalistic month (perigean effects). This is certainly encouraging if tidal rhythmites are, indeed, proxies of tidal conditions. Archer cautioned, however, “It is not yet completely conclusive whether the rhythmite signatures are complete records of tidal activity or whether they are a reflection of partial preservation of ancient tidal cyclicities” (Archer et al., 1995, p. 415).

Subsequent research addressed the applicability of tidal rhythmites in surmising ancient tidal parameters. Archer and Kvale utilized predicted tidal heights in modern systems to surmise, via periodogram analysis, the periodicities present in the ancient rhythmite series (Kvale et al., 1995; Archer, 1996). While sedimentation models based on these data were not recapitulated, subsequent analyses of actual rhythmites from the Pennsylvania Mansfield and Brazil Formations were made, and the results then compared to those given by the predicted tidal heights. The predicted tidal heights in this study were time-abstracted by being cast into an “event series,” in accordance with the record of tides present in tidal rhythmites. The results of the study indicated compatibility between the time-abstracted tidal heights and the tidal rhythmites. It is important to note that the rhythmites may not have been of sufficient age for neap-spring periods to differ significantly from modern periods. Spectral analysis revealed apparent annual cycles in both formations and what appeared to be tropical and synodic periods in the Hindostan Whetstone Beds of the Mansfield Formation. These results complemented the work of previous research, whereby short segments of well-formed rhythmite data from a number of sites were subjected to similar scrutiny (Archer, 1996). These data were obtained from nine separate localities and three time periods, and include three European Miocene sections, 4 North American Carboniferous sections, and two Late Proterozoic sections, one from Australia and the other from Utah, USA. The periodograms of the raw data indicated that the tidalites exhibited synodic neap-spring cycles that were often distorted, as peak periodicities ranged from 7.45 bundles/cycle to 28.95 bundles/cycle. This variability is likely a function of two variables: 1) the record lengths of the rhythmite series were short, ranging from only 32 to 208 laminae, and 2) many of the records did not represent a continuum of deposition.

The Precambrian Elatina Formation from Australia revealed rhythmic mm-scale laminae similar to that observed by Kvale and Archer (Williams, 1989, 1990, 1997, 2000). The study of these rhythmites yielded some of the first precise values of ancient tidal periodicities from the stratigraphic record. While some of the rhythmites from the Elatina Formation were initially thought to be varves recording Sunspot cycles (Williams and Sonett, 1985), evidence suggested that these rhythmite data preserve long continuous records of tidal deposition for up to 60 years (with data from several cores).

The Elatina record was comprised of three incomplete records obtained from 10-m-thick drill cores. This composite record contained what were interpreted to be 1580 neap-spring cycles, representing about 60 years of deposition. Comparison of this data with modern tidal station data from Townsville, Queensland, showed strong similarities (Fig. 10). A regular pattern of fortnightly inequalities (differences in height of spring tide peaks) can be observed in both. This is related to the perigee/apogee effects superimposed onto the synodic month. The deposits exhibit a variation in the pattern of the neap-spring peaks that is observed roughly every 26.2 neap-spring cycles. Interestingly, this is about the length of a solar year. It has been observed that the highest sea levels of the year usually occur in the autumn, due to a combination of atmospheric pressure, wind, and water temperature effects (Komar and Enfield, 1987). Lesser, second-order peaks are observed, as well. These are thought to be related to the semianual cycle of the Sun’s declination; high spring tides are

Fig. 10. Multi-year tide and tidal rhythmite records from Australia. Top: Diurnal laminae thicknesses from the Elatina Formation. Neap-spring and lunar months are clearly discernible. Bottom: Tidal gauge record of maximum daily tidal heights from Townsville, Queensland. A neap-spring inequality is observed in both records (from Williams, 2000).
seen around the autumnal and vernal equinoxes, when the Sun is over the equator.

The Reynella Siltstone rhythmites from within the Elatina Formation contained 14–15 diurnal laminae in each neap-spring cycle. This compares well to the Elatina rhythmites, where pairs of neap-spring cycles contained a maximum of 29 diurnal laminae. Thus, each record was interpreted to possess 29–30 lunar days per synodic month, which implies approximately 30–31 solar days per synodic month (Archer et al. (1991) note that care must be taken when employing the maximum number of events, as employing this method in modern systems can yield days-per-year values that exceed 460 in some cases). The 26.2 neap-spring cycles per year found in the Elatina record indicate approximately 13.1 synodic months per year at the time of the tidalite formation. Therefore, Williams calculated \((30.0 \pm 0.5)^{\ast} (13.1 \pm 0.1) = 400 \pm 7\) solar days per year and a length of day of 21.9 ± 0.4 h at ~620 Ma.

One of the primary objectives of studies such as this is to surmise the early dynamics of the Earth–Moon system. The construction of a lunar recession curve is yet to be realized, although partial results are available (Fig. 11). The manner of lunar recession through time also influences ideas regarding the formation and subsequent early states of the Moon. However, “uncertainties in the available Paleoproterozoic paleotidal values are too great to permit a reasonable estimate of the Earth–Moon distance at 4.5 Ga” (Williams, 2000, p.56).

With the neap-spring period (and, thus, duration of the sidereal month) given by tidal rhythms, calculation of the past Earth–Moon distance is possible. The most common method, first employed by Deubner (1990), utilizes Kepler’s third law:

\[
\left(\frac{T}{T_0}\right)^2 = \left(\frac{a}{a_0}\right)^3,
\]

where \(T\) and \(T_0\) are the past and present values of the sidereal month and \(a\) and \(a_0\) are the past and present lunar distance (along the semi-major axis). Two less commonly used methods were presented by Williams. These methods are dependent on approximations of ancient lunar nodal periods, inclination of the lunar orbital plane, and changes in angular momentum of the Earth’s rotation and the Moon’s orbit. The first employs the equation for precession of the lunar orbit

\[
P = P_0(\cos i_0 / \cos i)(a/a_0)^{1.5},
\]

where \(P\) and \(P_0\) are the ancient and modern lunar nodal periods, \(i\) and \(i_0\) are the past and present inclinations of the lunar orbital plane to the elliptic plane, and \(a\) and \(a_0\) are the past and present lunar semi-major axes. The second less frequently used method uses the expression for change in lunar orbital angular momentum:

\[
1.219 - (\omega / \omega_0)^{4.93} = \left(\frac{a}{a_0}\right)^{1/2} + (0.46)^2 / (13(a/a_0)^{13/2}),
\]

where \(\omega\) and \(\omega_0\) are the past and present rotation rates of the Earth (Deubner, 1990). All three techniques, employing different values from the data sets yielded very similar values (ranging from 0.965 ± 0.005 to 0.969 ± 0.017 Earth radii). Given this data for the ancient lunar semi-major axis, a mean rate of 2.17 ± 0.31 cm/yr is calculated for the last 620 million years.

It is important to note that the sidereal period obtained from the rhythmite record is generally given in lunar days (a depositional event occurs once or twice in a lunar day). The length of the day, however, has changed considerably through geologic time as the Earth’s rotation has slowed, and is an inconsistent temporal unit. Caution should be exercised when periods given in terms of “days” or other units with inconsistent temporal reference frames are used in calculating ancient parameters. To make the conversion from a period expressed in units dependent on Earth’s rotation to a period given in a timeframe independent of tidal dissipation effects, it is necessary to make assumptions regarding both the angular momentum of the Earth–Moon system rotation and Earth’s moment of inertia when using sub-yearly data (Coughenour and Lacovara, 2005). Multi-year records, such as those provided by the Elatina and Reynella rhythms, may provide the data necessary to falsify or further justify these hypotheses (see Section 2.6).

The banded iron deposits of the Weeli Wolli Formation, dating to ~2.5 Ga from Western Australia, have proven difficult to interpret and are instructional in revealing the potential pitfalls of tidal rhythmite analysis (see discussion in Williams, 2000). Laminae couples were originally interpreted as each representing one year (Trendall, 1973; Walker and Zahnle, 1986). From this interpretation, a mean periodicity of approximately 23 couples (years) per cycle was estimated. Although the absence of an 11 year cycle excluded a 22 year Sunspot cycle, Walker and Zahnle believed the laminae preserved what is now the 18.6 year nodal cycle (this is the variation of the Moon’s orbital plane about the ecliptic, or plane of the Sun’s orbit about the Earth). This cycle does appear in certain modern climate records, such as temperature and rainfall data from Western North America and tree-ring data from Patagonia, and is also observed in modern tidal height data. The lunar nodal cycle has been qualitatively noted to affect sedimentation patterns (Oost et al., 1993). Calculation of the Earth–Moon distance for \(P = 23.3\) years, yielded \(a / a_0 = 0.86 ± 0.1\) at 2450 Myr BP. These results, interestingly, are similar to the results produced when the couples are interpreted as each representing a neap-spring cycle, and a periodicity of 28 to 30 laminae per cycle is estimated (Williams, 2000).

The current high rate of recession is nearly twice the average for the past 620 Myr. By looking backward in time, only the 1.47 ± 0.46 cm/yr scenario, suggesting that the Moon has never made a close approach to Earth, seems to be in agreement with evidence suggesting lunar formation well before 3.2 Ga. From his analyses, Williams (2000) surmised that there has been little change in the Earth’s moment of inertia since the late Neoproterozoic (620 Ma), consistent with the analysis of Runcorn (Runcorn, 1964) and the model assumptions used by Hansen (1982).

Data from the Precambrian Australian rhythmites were somewhat unique, in that they represented multi-year tidal records. Frequently, rhythmite sections are found representing only months or weeks of deposition. Furthermore, many rhythmites contain discontinuities due to erosion, bioturbation, or other factors previously discussed. Thus, when complete rhythmites are found, extraction of tidal periodicities from sub-yearly sets is paramount. Analysis of a 5.5 month-long continuum of Carboniferous tidalites from the Brazil
Formation reveals the potential efficacy of sub-yearly data in surmising accurate lunar periods (Kvale et al., 1999). The study also provides useful insights into the refinement that raw data may need, before performing spectral analysis. The Brazil Formation rhythmites were deposited in a mixed-diurnal system that became semidiurnal during neap tides. This effect is observed in modern systems, and is related to basin resonance effects (basin resonates with semidiurnal tidal constituents). A diagnostic test for the continuity of the system was performed. This consisted of checking for a regular pattern of “crossovers” in the neap tides. Crossovers are caused by equatorial passage of the Moon, and result in consecutive semidiurnal high tides that are virtually the same in magnitude. This regular pattern of crossovers is observed, indicating the likely continuity of deposition (Fig. 12). Harmonic analysis of such a record yields periodicities with units of tidal events resulting in deposition per cycle. Subordinate laminae in the semidiurnal portions of the record were removed to yield equidistant sampling at presumably one lunar day (assuming continuous deposition/preservation). This may be problematic around neap cycles, where subordinate semidiurnal laminae may be difficult to differentiate from diurnal laminae; incorrect removal would result in a frequency shift in the ensuing spectral analysis. The periodogram yielded a peak at 13.64 laminae with a relatively low power spectral density (Fig. 13). In diurnal systems the tropical half-month controls semimonthly periods. Thus, the value given by harmonic analysis was interpreted as corresponding to the tropical half-month. In comparison, modern tropical half-months are 13.66 modern solar days. Conversion to the sidereal period is necessary once the lunar period is calculated. Kvale et al. provided a simple approximation to do this for Phanerozoic (545 Ma to present) data, and presented evidence that the conversion has changed little through time, as all lunar periods have shortened only slightly. The methodology used in the conversion from the synodic month to the sidereal month is outlined by (Archer, 1991). Runcorn (1979) also presented a method for the conversion if the number of solar days per year is known. The conversion from the tropical period is simply 1:1, as the tropical and sidereal periods are nearly equal (27.32 days and 27.3186 days, respectively).

Other studies employing similar methodologies to those of Kvale et al. and Williams soon followed. Berger et al. analyzed sediments from the Santa Barbara Basin since 1120 A.D. for total organic content (TOC) variations, 1200 A.D. for fish scale abundance, and 1350 A.D. for varve (laminae) thicknesses (Berger et al., 2004). Spectral analysis of each of these yielded several periodicities, including a 17.7 year-cycle in the varve thicknesses that may be correlated to the 4.425 year perigee cycle (4 × 4.425 = 17.7) and a 37.4 year cycle in TOC flux that may correlate to the 18.6 year nodal cycle. In fact, Berger et al. note, “A surprising number of the varve and TOC cycles can be interpreted as deriving from the common tidal cycles” (Berger et al., 2004).

The interpretation of Precambrian deposits often offers intriguing possibilities and challenges. Aside from the generally reduced amount of record compared with more recent eras, difficulties associated with metamorphism are often encountered. Eriksson and Simpson (2000),

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Fig. 12. Laminae thickness record from the Brazil Formation (Pennsylvanian) exhibiting a regular pattern of crossovers (diurnal inequality nearly zero corresponding to low lunar declination) (from Kvale et al., 1999).

Fig. 13. Results of spectral analysis of the diurnal record from the Brazil Formation. The dominant peak corresponds to 13.64 events (~lunar days), representing the tropical half-month (from Kvale et al., 1999).
reanalyzed the metamorphosed 3.2 Ga Moodies Group deposits composed of cross-bedded sandy foreset beds. The record exhibited a small sample size and high degree of variance with respect to the number of laminae per purported cycle. The authors reported tidal periodicities of 9.33 and 2.21 beds/cycle in the thicknesses.

Tidal rhythmites from the Paleoproterozoic (2.5–1.6 Ga) in India are among the first to be analyzed from the Indian subcontinent (Mazumder, 2004). The Chaibasa strata have undergone metamorphism; however, the interbedding of sandstones and shales is still evident in the greenschist facies. It was claimed that laminae thicknesses can still be a tidal proxies if the laminae are metamorphosed in a uniform manner. Raw data were subjected to spectral analysis, revealing an approximate period of 32 semidiurnal deposits/neap-spring cycle, implying ~32 lunar days/synodic month. It should be noted, however, that this periodicity is only reliable in series that are continuous. Inspection of the plots suggests frequent interruptions in the thick–thin pairing of the diurnal inequality that are too frequent to have arisen from only crossovers and likely best explained by missing laminae.

The Big Cottonwood Formation of Utah, dating to 900 Ma, has been interpreted as possessing daily, monthly, and yearly cycles (Chan et al., 1994; Sonett et al., 1996; Sonett and Chan, 1998). The clay-draped, quartzite laminae appear to lack a diurnal inequality and the number of laminae in what have been interpreted as neap-spring cycles is highly variable, making assessment of the continuity of the signal potentially problematic.

3.6. Implications of tidal rhythmites

The fact that a variety of conditions may lend themselves to the formation of tidal rhythmites is encouraging for several reasons. Primary among these is the possibility that rhythmites may aid in description of not only the environment of deposition (tidal or non-tidal), but also the sub-environment (intertidal or subtidal). To this end, rhythmites may encode non-tidal information if the particular sub-environment was under the influence of non-tidal forces, such as basin geometry, climate, or certain biological factors. That tidal rhythmites may yield clues regarding paleoclimate may be of particular interest to paleobotanists and/or paleontologists. Typically, estimates of paleoclimatic variables (e.g. MAT, precipitation trends, etc.) are based on paleolatitude data, floral or faunal evidence, or climate-specific lithologies. These typically yield a broad sense of the environment, but often lack detail. Analysis of deviations from predicted tidal influences within rhythmites may yield climatic detail, if yearly timeframes can be established in the particular rhythmite data. Several studies by Kvale of his observations of Pennsylvanian-aged units have affirmed the potential utility of tidal rhythmites in interpreting non-tidal variables. In particular, he postulates that rhythmites may indicate seasonal precipitation trends (Kvale et al., 1994). Annual data of neap–neap thicknesses from the Hindostan Whetstone Beds display a bell curve pattern that deviates from the expected two-peak semiannual cycle seen in the Brazil Formation. Kvale hypothesized that this is likely due to seasonal changes in river discharge that caused fluctuations in sediment supply (modern data suggest wet season discharges result in an increase of sediments that may be deposited). Smith et al. (1990) also noted that stream discharge into the glaciomarine delta was a variable, affecting suspended sediment concentrations, and, thus, sedimentation (Fig. 14).

4. Conclusion

In the review presented, research of tidal processes and their effects on sedimentation has been summarized. In particular, the
tidally-forced sedimentological features preserving various luni-solar periodicities known as tidal rhythmites were the primary focus of this paper. The study of tidal rhythmites has proven useful to scientists in recent years attempting to extrapolate the history of Earth–Moon dynamics from the geologic record. The fact that rhythmites have been recognized throughout geologic history up to 3.2 Ga offers scientists the chance to study tidal processes, and their relative changes, as the Earth has matured. This raises the possibility for interesting new research. Paleogeographic and paleoenvironmental reconstructions based on tidal rhythmites/bundles may be possible, as the mere recognition of these deposits likely indicates an intertidal or subtidal environment of deposition. In addition, deviations from expected tidal periodicities may indicate seasonal trends, such as variations in precipitation (Kvale et al., 1994) or temperature (Smith et al., 1990), further aiding paleoenvironmental studies.

Tidal rhythms are essential if hypothesis testing of numerical models of the Earth–Moon system and its evolution is to proceed. Other data, such as stromatolites and fossil corals, provide only limited resolution of relatively recent (post-Devonian) tidal records. Models presented since the 1970s have incorporated a number of variables into the governing equations (HDE's and Laplace's equations) that offer precise approximations of the luni-solar tides' effects on the Earth. In particular, researchers attempted to reconstruct bathymetry and continental configurations of the ancient Earth, as dissipative processes occur at the interface between continents and ocean waters. To this end, the two-depth model was employed (Suessermann and Brosche, 1978). This model assumes that the extent of ancient shelf areas was known (and the average depth of water over these areas), as well as the average deep ocean depth. Hansen, employing such a bathymetric model, and assuming a rigid, spherical Earth with no net dissipation between the Earth and Moon, found a lunar orbit well beyond the Roche limit at 4.5 Ga. He also found evidence that dissipation was half of that seen today when the length of day was 20 or less. He postulated that this was due to resonance between the $M_2$-tide and the oceanic normal mode (eigen-frequency).

The data, the tidal rhythmites, are part of an interesting story of sedimentologic research. Since the seminal studies of intertidal deposits by Richter and Haentschel in the 1920s and 1930s, progress has been made in gradual steps that outlined the processes and features of modern tidal sedimentation. In particular, the post-war boom of the 1950s and 1960s realized more quantitative theories and models that probed into possible links between tidal cycles and sedimentation (Allen and Narayan, 1964; Reineck and Wunderlich, 1968; Terwindt and Breusers, 1972). Some authors even hypothesized that individual sand and mud laminae could be deposited during a single tidal cycle, with sand deposition occurring during flood tides (or ebb tide, if dominate over the flood tide) and mud deposition occurring during slack water (Reineck, 1976). However, it was not until 1980 that neap-spring cycles were observed in the depositional record (Visser, 1980). Soon thereafter, tidal periodicity was observed in the ancient stratigraphic record (Allen, 1981). These studies presented since the 1970s have incorporated a number of variables into the governing equations (HDE's and Laplace's equations) that offer precise approximations of the luni-solar tides' effects on the Earth. In particular, researchers attempted to reconstruct bathymetry and continental configurations of the ancient Earth, as dissipative processes occur at the interface between continents and ocean waters. To this end, the two-depth model was employed (Suessermann and Brosche, 1978). This model assumes that the extent of ancient shelf areas was known (and the average depth of water over these areas), as well as the average deep ocean depth. Hansen, employing such a bathymetric model, and assuming a rigid, spherical Earth with no net dissipation between the Earth and Moon, found a lunar orbit well beyond the Roche limit at 4.5 Ga. He also found evidence that dissipation was half of that seen today when the length of day was 20 or less. He postulated that this was due to resonance between the $M_2$-tide and the oceanic normal mode (eigen-frequency).

It appears that research of tidally influenced deposition continues to mature, with progressively refined studies finding publication. Currently, there is interest in finding and understanding suitable modern analogs to the stratigraphic data. Studies in this realm should clarify some of the more subtle issues hindering progress in the interpretation of ancient sediments, particularly the resolution of temporal references within the event series. Analyses of modern systems, tidal constituents represented in tidal rhythmites (Kvale, 2006), and the emerging field of waveform analysis may offer solutions to these problems. Much work remains in assembling a more comprehensive view of the mechanisms relevant to the dynamics of particular depositional sub-environments. The spatial and temporal diversity in the record is substantial, but the potential knowledge of Earth history that may be unlocked is likewise substantial. Ultimately, the interpretation of tidal deposits may lend information that enables researchers to gain insights into paleogeography, paleoclimatology, paleoenvironments, stochastic processes, the relation between dissipation and continental configuration, the relation between tides and seismic activity, and still other topics yet to be pursued.

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