Sedimentary Geology 295 (2013) 67–76

Contents lists available at ScienceDirect

Sedimentary Geology

journal homepage: www.elsevier.com/locate/sedgeo

Calculating Earth–Moon system parameters from sub-yearly tidal deposit records: An example from the carboniferous tradewater formation

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ARTICLE INFO

Article history:
Received 25 April 2013
Received in revised form 31 July 2013
Accepted 1 August 2013
Available online 8 August 2013

Editor: J. Knight

Keywords:
Sedimentology
Tidal deposits
Tidal rhythmites
Illinois Basin
Tidal friction

ABSTRACT

The secular evolution of the Earth–Moon system remains poorly constrained, largely because there are few continuous tidal rhythmite or foreset bundle sequences that preserve deposition over more than several neap–spring tidal cycles. Deposits recording less than one year of deposition do not facilitate direct calculation of past lunar distance directly from Kepler's Laws, but may prove necessary to reconstruct lunar orbital evolution because they are far more common than longer records. A method is demonstrated to make use of shorter tidal deposit sequences by utilizing conservation of angular momentum between the Earth and Moon and estimating the solar component of tidal deposition, while assuming a constant moment of inertia for Earth since the Proterozoic. The precision and accuracy of spectral estimates obtained from short records are considered, as are the limitations of subsequent calculations of Earth–Moon parameters.

The Late Carboniferous Abbott sandstone of the Tradewater Formation in the Illinois Basin preserves just over 6 apparently continuous neap–spring cycles in its semidiurnal deposits. The quality of these data, as assessed via sedimentological evidence and statistical time series properties, produces spectral estimates that are likely within at least $\pm 5\%$ of the actual underlying periodicity (90% accuracy). To test the usefulness of such records, we assessed the possible scenarios of 90% and 95% accuracy. At 90% accuracy, the error bounds on Earth–Moon parameter estimates become rather large and render individual data sets to be of limited use. At 95% accuracy, very general inferences about the evolution of the Earth–Moon system may be made. Calculated mean lunar orbital distance at 315 Ma is 3.798×10^8 m with error bounds of -0.086×10^8 m and $+0.046 \times 10^8$ m. We conclude that short sequences of cyclic tidal deposits offer rather limited resolution of lunar distance estimates. Utilizing multiple sub-yearly data of similar age in ensemble may prove necessary if further investigations of secular changes in Earth–Moon parameters are to proceed.

1. Introduction

1.1. Tidal dissipation and Earth–Moon dynamics

The compilation of a comprehensive history of the Earth–Moon system has proven difficult because of uncertainties regarding the nature of tidal dissipation (Lambeck, 1980; Brosche, 1984), lack of reliable stratigraphic/paleontological chronometers (Coughenour et al., 2009), and the complex character of Earth's orbital motion (Laskar, 1999). Lunar retreat is caused by a transfer of angular momentum from Earth's axial rotation as the Earth is slowed by tidal dissipation (Munk and MacDonald, 1960). The lunar orbit gains the angular momentum lost by Earth, which increases the lunar distance to Earth. The precise nature of tidal dissipation has been a long-standing problem in physical oceanography, although advances in satellite altimetry and numerical modeling have resolved many components of the problem (Egbert and Ray, 2000). Recent models of tidal dissipation now generally indicate turbulence in the bottom boundary layers, as well as dissipation owing to internal waves and near-surface turbulence as the water body is displaced by tidal forces (Thorpe, 2004). Solid Earth tides are largely ruled out as major dissipative agents at present (Suendermann and Brosche, 1978), although it is hypothesized that they were a primary factor very early in Earth's history (Webb, 1982). Ocean–tidal dissipation models are constrained by lunar laser ranging, satellite perturbations, and changes in the length of day that indicate that overall ocean dissipation due to the Moon and Sun is about 4 TW, with the M2 tidal constituent accounting for 2.5 TW (Munk, 1997).

Calculating tidal dissipation in the geologic past is much more problematic. Constraining data and boundary conditions, such as lunar

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http://dx.doi.org/10.1016/j.sedgeo.2013.08.001

retreat rate, Earth's rotation rate, Earth–Moon distance, continental configuration, bathymetry, and sea level are difficult to quantify with a high degree of precision throughout geologic history (see summaries in Munk and MacDonald, 1960; Suendermann and Brosche, 1978; Lambeck, 1980). Furthermore, it is apparent that lunar retreat rate and, thus, dissipation have not been constant through time. Lunar laser ranging has placed the current lunar retreat rate at 3.82 cm/year (Dickey et al., 1994). Assuming this value as constant over the past two billion years yields a lunar distance of just several Earth radii that is within the Roche limit marking the onset of significant disruption of the Moon (including mass loss and significant heating) by Earth's gravitational field (e.g., Munk, 1968). There is no evidence for such a catastrophic event at that time (Williams, 2000). Analysis of lunar material suggests that lunar formation resulted from a planetesimal collision with the Earth during the Hadean (Hartmann and Davis, 1975; Cameron, 1986). Empirical data, such as tidal deposits preserving Earth–Moon parameters, seem to be required in conjunction with ocean and orbital evolution models if past tidal dissipation is to be understood (Bills and Ray, 1999).

1.2. Tidal rhythmites/bundles

Biological chronometers, such as growth lines on corals and bivalves (e.g., Wells, 1963; Berry and Barker, 1968), are plagued by lack of precision due to complex environmental and bio-genetic factors (e.g., Williams, 2000). Lunar–solar cycles appear best preserved in tidal rhythmites (composed of vertically accreted planar deposits) and tidal bundles (composed of laterally accreted foreset bedforms) (Archer, 1995; Allen, 2004). The continuity and record length of such cyclic tidal deposits are essential in extracting precise estimates of past Earth–Moon parameters (Coughenour et al., 2009).

Lunar distances have been calculated from tidalites deposited over the course of multiple years. This has been done for the Elatina Formation of southern Australia (620 Ma) (Williams, 2000) and attempted for the Big Cottonwood Formation of Utah (900 Ma) (Sonett et al., 1996; Sonett and Chan, 1998). The Elatina Formation is of particular interest, as it appears to preserve a continuous record of 1580 neap–spring cycles representing more than 60 years of deposition (Williams, 1989). The Elatina Formation rhythmites are found in the Adelaide fold belt of southern Australia and are interpreted by Williams (1989) to have been deposited in a distal ebb tidal delta setting. The rhythmites are composed of graded siltstone and fine-grained sandstone laminae generally capped by thin mud drapes. The comparatively thick laminae of spring tidal cycles are primarily diurnal, although some laminae contain thinner sub-laminae that may indicate at least some semidiurnal deposition in a mixed tidal regime. Most subordinate semidiurnal deposits may have been filtered out due to insufficient tidal current velocities. Neap tidal cycles contain thin, abbreviated laminae and a greater mud fraction, with some sections preserving very few to zero laminae and a thick mud drape. Although daily deposition is not recorded, the monthly inequality of spring tides is preserved in the Elatina Formation.

Multi-year records have the advantage of not requiring perfectly continuous preservation of twice-daily deposits, as neap–spring cycles per year can be counted. For instance, direct calculations of Earth–Moon distance are possible from the Elatina Formation by finding the number of neap–spring cycles per year and, subsequently, the number of sidereal months per year. With these periodicities available Kepler's third law can be applied directly to find Earth–Moon distance. The lunar distance calculated from the multi-year Elatina Formation at 620 Ma is 3.709e8 ± .019e8 m (Williams, 2000).

Tidalites spanning less than one year of deposition are more common, but present several challenges. First, the longest periodicity reliably preserved in shorter records is either the synodic or tropical month. To extract this cyclicity via spectral analysis, each dominant tidal event (either the flood or ebb tide) must be represented by a foreset deposit. Missing deposits rapidly decrease the apparent period of the neap–spring cycle, introducing large errors into the estimate. Another challenge posed by short records is the lack of temporal reference for the length of day and, therefore, no direct calculation for lunar distance, which has inhibited earlier studies (Kvale et al., 1999). A complete discussion of the problems associated with calculating Earth–Moon parameters from imperfect tidalite records is given in Mazumder and Arima (2005) and ensuing comment/reply in Williams (2005) and Mazumder (2005). Coughenour (2009) has shown that, despite these problems, by employing appropriate spectral estimation techniques it is possible to calculate the neap–spring frequency to an accuracy of 90–95% for continuous (or very nearly so) records of 6 or more neap–spring cycles.

Runcorn (1979) derived a method to calculate past Earth–Moon distances from sub-yearly paleontological data (originally applied to invertebrate growth lines) using tidal dynamics. The derivation is valuable to consider, and provides an excellent starting point for using sub-yearly data. Unfortunately, there are several assumptions and calculations in the manuscript that are not fully explained or referenced. Eqs. (10)–(12) in Runcorn (1979) employ a dynamical approximation from Jeffreys (1976), but with no reference or explanation provided (see Lyttleton, 1980). These approximations are critical, especially for the frequency-dependent lag-angle scenario, as otherwise there is no solution to the problem without knowledge of the ratio of past length of the sidereal day to the present length. The simpler independent lag-angle scenario is also considered, but provided in a form that requires multi-year geochronometer data. The evolution of the tidal lag angle is still uncertain, as is the general evolution of dissipative mechanisms (e.g., Kagan and Suendermann, 1996; Sonett et al., 1996). Goldreich (1966) posited that dynamical evolution of the Earth–Moon system is not greatly different whether constant lag is assumed or if it is treated as frequency-dependent. For the sake of transparency, and because the solutions given by the independent and frequency-dependent lag-angle scenarios are thought to be similar, the independent lag-angle approach is used herein.

Using the above work, we seek to provide a transparent methodology to calculate temporal reference (length of day) and lunar distance from short tidalite records using the fundamental considerations of angular momentum conservation and Kepler's laws. An example is provided to demonstrate the method and provide a new data point for length of day and lunar distance in the Carboniferous Period from the Tradewater Formation.

1.3. Abbott sandstone (Tradewater Formation) tidal bundles

The interior coal basins of the U.S. Midcontinent were deposited during the Pennsylvanian Period. These basins include the Western Interior and Eastern Interior basins (Fig. 1). Historically, no deposition in these basins was attributed to tidal influence, but rather to non-marine fluvial–deltaic environments. The recognition of neap–spring and semidiurnal variations in bed thicknesses along with sedimentological evidence, such as grain size trends and sand/mud couplets similar to those observed in modern tidally-influenced environments, has resulted in re-interpretations of a number of interior basin facies (e.g., Kvale and Archer, 1990; Archer and Greb, 2012). The Western Interior Basin has yielded notable tidalites in the Ireland and Tonganoxie Sandstones (Archer et al., 1994; Archer and Greb, 2012). The Eastern Interior Basin (or 'Illinois Basin') has proven even richer in cyclic tidal deposits, with examples from the Brazil Formation (Kvale and Archer, 1990), Francis Creek Shale (Kuecher et al., 1990), and Hindostan whetstone of the Mansfield Formation (Kvale et al., 1989). Tidal rhythmites from several of these units, such as the Brazil Formation (Kvale et al., 1999) and the Mansfield Formation (Sonett et al., 1996), have been utilized in Earth–Moon studies, although the application of the former has been limited due to a mixed diurnal/semidiurnal regime and the latter limited by shorter record length.