Implications of lunar orbital periodicity from the Chaibasa tidal rhythmite (India) of late Paleoproterozoic age

Rajat Mazumder*
Department of Geology, Asutosh College, Kolkata 700 026, India

ABSTRACT

Harmonic analysis of the sandstone foreset-laminae thickness series from the Chaibasa tidal rhythmite, India, clearly shows that a normal semidiurnal tidal system with synodic month of ~32 lunar days was in effect during the late Paleoproterozoic (2100–1600 Ma). The minimum number of solar days in a lunar sidereal month was ~31. Published quantitative tidal-rhythmite data of others in combination with data derived from the Chaibasa tidal rhythmite indicate long-term stability of the lunar orbit and progressive increase in the Earth-Moon distance during the Proterozoic.

Keywords: tidal rhythmite, tidal cycles, lunar orbital periodicity, Earth-Moon system, Paleoproterozoic, Chaibasa Formation.

INTRODUCTION

Tidal rhythmites are vertically and/or laterally stacked thin beds or laminae, usually of sandstone, siltstone, and mudstone, that exhibit rhythmic thickness variations as a consequence of strong lunar-solar tides (Williams, 1989; Kvale et al., 1999). Analysis of tidal rhythmites coupled with an understanding of tidal theory provides valuable information on paleo–lunar orbital dynamics and the ancient Earth-Moon system (Williams, 1989, 2000; Archer et al., 1991; Sonett et al., 1996; Kvale et al., 1999). Tidal periods have been documented in rocks as old as 3200 Ma (Eriksson and Simpson, 2000). As Williams (2000) pointed out, careful study of Precambrian tidal rhythmites promises to illuminate the evolving dynamics of the early Earth-Moon system. Although high-quality tidal-rhythmite data are available from the Neoproterozoic (Williams, 1989, 2000; Chan et al., 1994; Sonett et al., 1996; Archer, 1996), similar data are unavailable from the Mesoproterozoic and rare from the Paleoproterozoic (Williams, 2000). Herein I report lunar orbital periodicity from the Chaibasa Formation (India) of late Paleoproterozoic age, along with the implications for the evolving Precambrian Earth-Moon system.

GEOLOGIC SETTING

The 6–8-km-thick, entirely siliciclastic Chaibasa Formation (Fig. 1) constitutes the lower part of the two-tiered Singhbhum Group, comprising rocks metamorphosed to greenschist (locally amphibolite) facies (Naha, 1965; Saha, 1994). Lithologically it is characterized by the interbedding of sandstones and shales in different scales. The Chaibasa Formation conformably overlies the 2100 Ma Dhanjori Formation (Roy et al., 2002a) and is unconformably overlain by the Dhalbhum Formation (cf. Mazumder, 2003). The 1600 Ma (Roy et al., 2002b) Dalma lava conformably overlies the Dhalbhum Formation of the Singhbhum Group (Bhattacharya and Bhattacharyya, 1970). The Chaibasa Formation is thus of late Paleoproterozoic age (cf. Mazumder, 2003). Lack of datable rock is the major impediment to determining the precise age of the Chaibasa Formation. Although the Chaibasa sandstones formed in a subtidal setting, the shales formed in a distal offshore setting and represent marine flooding surfaces (Bose et al., 1997; Mazumder, 2002). The Chaibasa succession is generally transgressive with intermittent punctuations caused by short-term lowstands during which sandstones were emplaced (Mazumder et al., 2000; Mazumder, 2002; cf. Cattaneo and Steel, 2003).

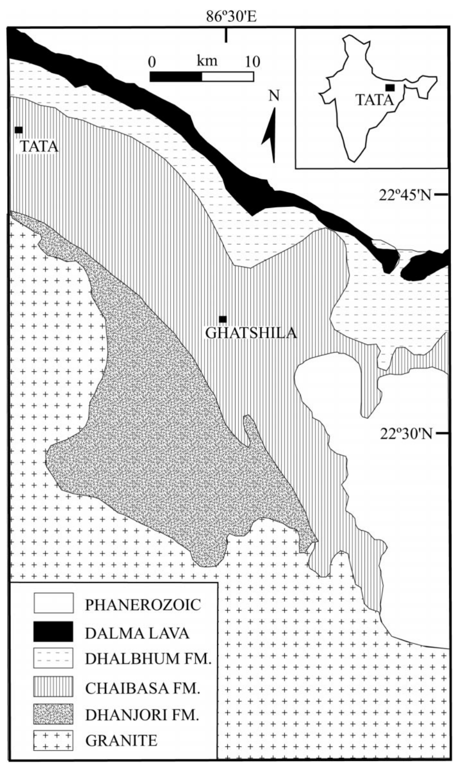


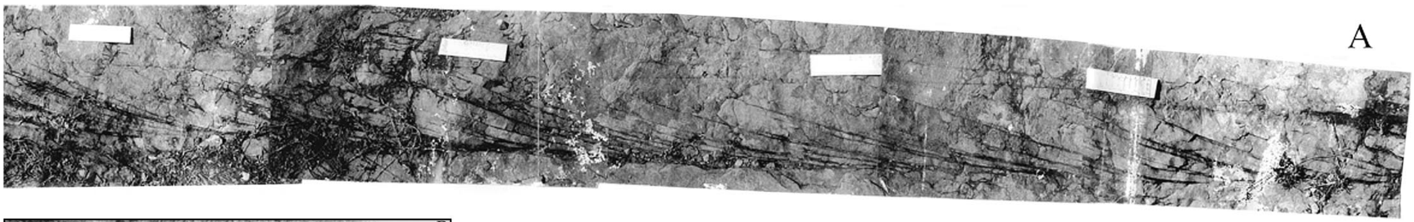
Figure 1. Geologic map of study area. Chaibasa and Dhalbhum Formations together constitute Singhbhum Group (simplified after Saha, 1994).

METHOD

Basic Data

The focus of this paper is a cross-bedded sandstone (Figs. 2A, 2B) best exposed in and around Ghatshila (Fig. 1). The sandstones are generally well sorted and internally characterized by unidirectional cross-strata (set thickness to 65 cm). The thick-thin laminae alternations are characteristic (Figs. 2B, 3A, and 4A), as is a double mud drape (Fig. 2B). In places, the cross-bed sets exhibit cyclic intraset variation in stratification style, from concave-up to planar to sigmoidal geometry (Fig. 2A); the sets are characterized by sandstone foresets separated by mudstone drapes (Fig. 2B). The abundance and thickness of mudstone drapes vary across the sets, showing an inverse relationship to the foreset thickness in the sandstone: drapes are thinner and relatively rare in intervals of thick foresets and abundant and thicker in intervals of thin foresets (cf. Tape et al., 2003). Laminae thickness is measured perpendicular to the dip of the foresets along a horizontal line between the upper and lower bounding surfaces. Cy-

*Present address: Geological Institute, EIS, Yokohama National University, 79-7, Tokiwadai, Hodogaya ku, Yokohama 240-8501, Japan; e-mail: mrajat2003@yahoo.com.



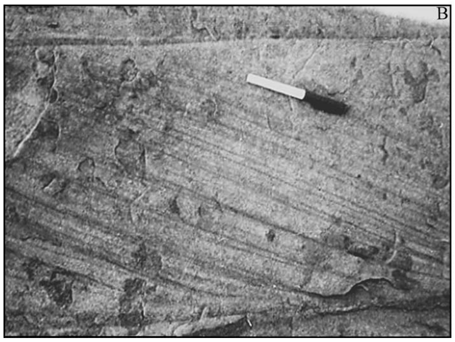
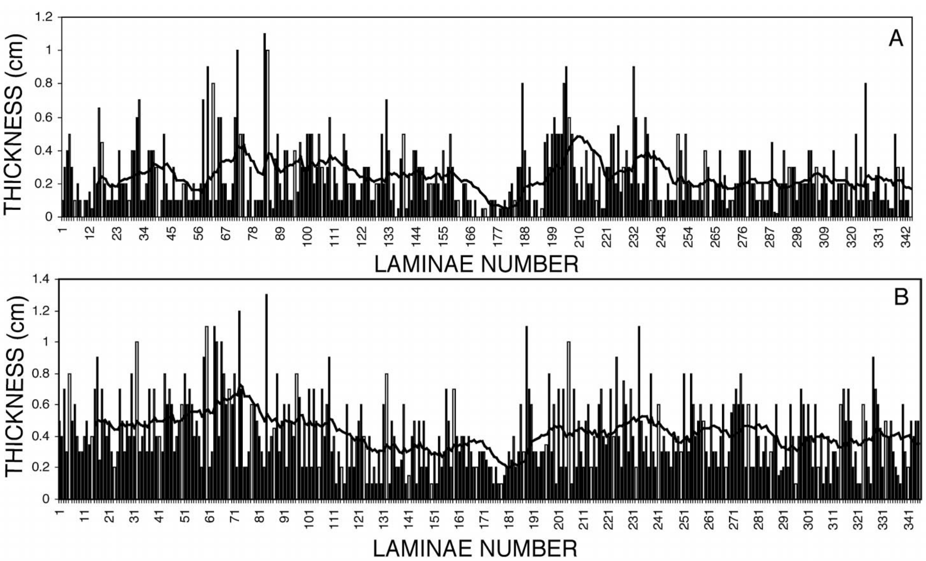


Figure 2. A: Cross-stratified Chaibasa sandstone showing variation in cyclic intraset cross-stratification style, from concave-up to planar to sigmoidal geometry (length of each scale is 16 cm). B: Chaibasa sandstone showing characteristic thick-thin laminae alternations and double mud drape (pen length is 12 cm).



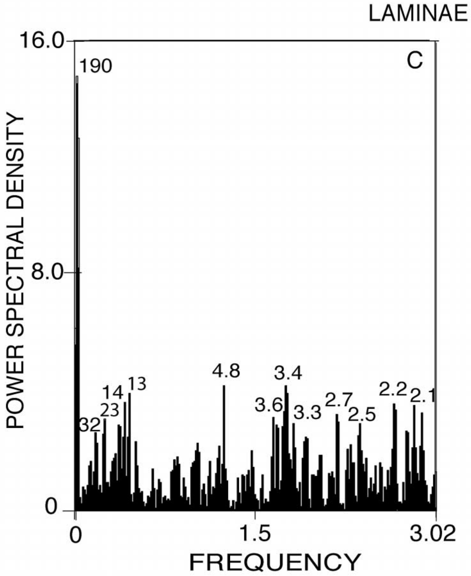


Figure 3. A: Rhythmic thickness variations in successive foresets within cross-stratified Chaibasa sandstone. B: Bar chart showing absolute value of difference between successive laminae thicknesses (following methodology of de Boer et al., 1989) presented in A. Semidiurnal signal is well reflected in both A and B. C: Fast Fourier transform power spectral-density plots (unsmoothed) obtained from data set presented in A. Note consistent spectral periods of ~32 and 2 events, respectively. Spectral period of 190 events possibly indicates some long-period tidal and/or nontidal variation. See text for explanation.

clicities are revealed in plots of two successive foreset-thickness data sets measured from different stratigraphic levels from exposures 1 km southeast of Ghatshila (Figs. 1, 3A, and 4A). Random meteorological events like storms may impart thick-thin alternations in environments that lack semidiurnal tidal influence. Alternatively, semidiurnal thick-thin laminae alternations may be disturbed by such meteorological events (cf. de Boer et al., 1989). A statistical test of the basic data has therefore been made, following the methodology of de Boer et al. (1989), that reveals a significant semidiurnal signal (Figs. 3A, 3B, and 4A). The number of foreset laminae, constituting neap-spring cycles, varies from 27 to 30.

Harmonic Analysis

Harmonic analysis following the methodology of Archer et al. (1991) and using a Fast Fourier transform (FFT) program (Horne and Baliunas 1986; Press et al., 1989) was performed on both data sets. The program tests for cyclicities and is capable of separating cycles having closely spaced periodicities. The output is expressed as an event/cycle in a frequency vs. power spectral-density plot (Figs. 3C and 4B).

INTERPRETATION

Power spectral-density plots show spectral periods of 32 events that represent neap-spring cycles, analogous to those derived from the analysis of modern tides as well as from the ancient record (Figs. 3C and 4B) (Archer et al., 1991; Kvale et al., 1995; Williams, 2000). Both the power spectra exhibit a spectral period of ~2. This result, coupled with the occurrence of alternating, millimeter-scale, thick-thin laminae (Figs. 2C, 3A, and 4A), corroborates a dominantly semidiurnal tide

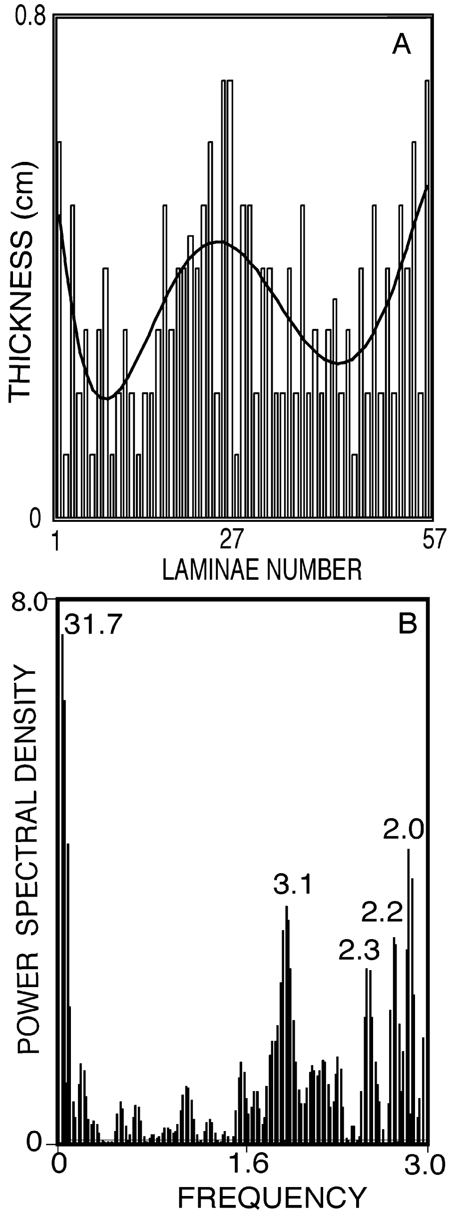


Figure 4. A: Bar chart showing thickness variation of successive foresets within Chaibasa sandstone (thickness data collected from subfacies D described in Bose et al., 1997). B: Fast Fourier transform power spectral-density plots (unsmoothed) obtained from data set presented in A. Note consistent spectral periods of ~32 and 2 events, respectively. See text for explanation.

during the Chaibasa sedimentation (cf. de Boer et al., 1989). Spectral peaks between 3–5 (Figs. 3C and 4B) and ~13 were likely generated by some random variations (storms?). The spectral peak at 23 might represent an abbreviated anomalistic period (cf. Archer, 1996; Kvale et al., 1999). The spectral period of 190 events possibly indicates some long-period tidal (abbreviated half-yearly cycle?) and/or nontidal variation (cf. Yang and Nio, 1985).

In a dominantly semidiurnal tidal system, synodic (spring–neap-spring) periodicity dominates tropical periodicity (Kvale et al., 1999). The laminae count reveals 27–30 laminae (events) constituting the neap-spring cycle during Chaibasa sedimentation. It is, however, difficult to recover the lunar orbital periods from the direct counting of laminae because periodically weak tidal currents (such as during neap tide), and random meteorological events (such as storms) may modulate or abbreviate tidal periods (de Boer et al., 1989; Kvale et al., 1999). However, both the power spectra show a consistent spectral period at 32 (Figs. 3C and 4B). Thus, there are ~32 laminae in a neap-spring cycle, implying at least 32 lunar days per synodic month during the Chaibasa sedimentation. It is interesting to note that Williams (2000) counted as many as 28–30 laminae couplets per neap-spring cycle on enlarged photographs of thin sections of little-compacted chert nodules (his Fig. 14a) up to 6–8 neap-spring cycles from the 2450 Ma Weeli Wolli banded-iron formation, Australia. Williams (2000, p. 54) considered only those cycles that are devoid of any sort of abbreviation. Williams (2000, his Table 1) calculated 31.1 ± 1.5 lunar days per synodic month during the early Paleoproterozoic. Thus, the minimum number of lunar days in a synodic month (32, Figs. 3C and 4B) and hence the minimum number of solar days per synodic month (~33 because the solar day is shorter than the lunar day; cf. Williams, 2000) during the Chaibasa sedimentation agree well with that calculated by Williams (2000, his Table 1).

Unlike the lunar synodic, tropical, and anomalistic periods, the lunar sidereal orbital period cannot be determined directly from the rhythmite record (Kvale et al., 1999, p. 1159; E.P. Kvale, 2003, personal commun.). In a dominantly semidiurnal tidal system, it is thus necessary to understand the relationship between the sidereal and synodic orbital periods (cf. Kvale et al., 1999). The present ratio of the lunar synodic (P_{syn}) to sidereal (P_{sid}) period is

$$P_{syn}/P_{sid} = 29.5271/27.3186 = 1.0808. \quad (1)$$

Kvale et al. (1999, p. 1159) proposed that this ratio can be safely used to convert from the synodic to the sidereal period over the past 1 b.y. The relationship between the lunar synodic and sidereal period is related to the three celestial body (Sun-Earth-Moon) problem, a long-standing question in astronomy, and may become clarified only on the basis of good-quality tidal-rhythmite data (P.L. de Boer, 2003, personal commun.). Williams (2000, his Table 1) calculated the number of solar days per sidereal month (sidereal period, t) during the Proterozoic from primary values derived from tidal rhythmites by applying following equation:

$$t = t_L/(1 + t_L/Y_D), \quad (2)$$

where t_L and Y_D are number of solar days per synodic month and year (cf. Runcorn, 1979), respectively. The number of solar days per year during the Chaibasa sedimentation is unknown, as is the precise age of sedimentation. There are no published quantitative late Paleoproterozoic (2100–1600 Ma) tidal-rhythmite data. However, a closer scrutiny of the lunar orbital periods derived by Williams (2000, his Table 1) from 620, 900, and 2450 Ma tidal rhythmites reveals that the ratio of the synodic to sidereal period ranges from 1.069 to 1.077. This fact, in turn, suggests that the variation of this ratio through geologic time was very small (cf. Kvale et al., 1999; Mazumder, 2002). The synodic to sidereal period conversion ratio of 1.07 is evident from the paleotidal and paleorotational data of the 2450 Ma Weeli Wolli Formation (Williams, 2000, his Table 1). By using a ratio of 1.07 as the synodic to sidereal period conversion factor, following the methodology proposed by Kvale et al. (1999, p. 1160–1161), the minimum number of solar days per sidereal month during the Chaibasa sedimentation is determined to have been ~33.0/1.07 = 30.8.

DISCUSSION

The pace of tidal evolution since ca. 450 Ma implies an Earth-Moon collision sometime between 2000 and 1500 Ma, resulting in total melting of Earth's mantle (cf. Lambeck, 1980; Walker and Zahnle, 1986). The obvious place to look for evidence of such a close approach and the catastrophic effects are mantle or deep-crustal rocks from that age, because before and afterward, normal tidal rhythmites would likely have formed. The Singhbhum Group overlies the 2100 Ma Dhanjori volcanic rocks and is overlain by the 1600 Ma Dalma volcanic rocks (ultramafic to mafic rare silicic lavas; cf. Roy et al., 2002a, 2002b; Mazumder, 2002, 2003; Mazumder et al., 2000; Mazumder and Sarkar, 2004). The Dhanjori volcanism took place in an intracontinental rift setting, as is evident from interbedded terrestrial deposits, and was a local phenomenon (Mazumder, 2002; Mazumder et al., 2000; Mazumder and Sarkar, 2004). The 1600 Ma Dalma plume upwelling, however, was part of a global tectonothermal event associated with attenuation and breakup of a Paleoproterozoic–Mesoproterozoic supercontinent (Roy et al., 2002b; Zhao et al., 2002, 2003). Thus, analysis reveals that a fairly normal semidiurnal tidal system similar to that of the present day was in effect during the late Paleoproterozoic

(2100–1600 Ma). Williams (2000, his Table 1) calculated the lunar semimajor axis (Earth-Moon distance, 54.6 $\pm$ 1.8 times Earth's radius) from the 2450 Ma Weeli Wolli banded-iron formation. Kvale et al. (1999, their Fig. 11) calculated the Earth-Moon distance and its secular variation for the past 900 m.y.; the Earth-Moon distance during the Elatina and Big Cottonwood sedimentation (620 and 900 Ma, respectively) was 3.70×10^{10} and 3.65×10^{10} cm, respectively. Williams (2000; his Table 1) calculated the Earth-Moon distance from primary values derived from the Elatina and Big Cottonwood rhythmite record as 58.16 $\pm$ 0.30 and 57.1 times the Earth's radius, respectively. Thus, published paleotidal and paleorotational data clearly indicate long-term stability of the lunar orbit and progressive increase in the Earth-Moon distance during the Proterozoic. Eriksson and Simpson (2000) attempted to quantify the oldest tidal record, which occurs in the 3200 Ma Moodies Group. However, Moodies spectral periods (23.6 and 13, Eriksson and Simpson, 2000, their Figs. 5A, 5B) are a combination of semidiurnal and diurnal signatures and cannot be considered for further mathematical treatment (cf. Eriksson and Simpson, 2001, p. 1160; Eriksson and Simpson [2004], however, suggested that the minimum number of lunar days in a synodic month during Moodies sedimentation was $\sim$20). Derivation of the lunar synodic and/or tropical periods during Moodies sedimentation is therefore difficult. Lack of quantitative evidence for lunar tidal forcing during Archean time thus is a major impediment to extending geoscientists' knowledge of the dynamic evolutionary history of the Precambrian Earth-Moon system (Williams, 2000; Mazumder, 2001).

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