Miocene semidiurnal tidal rhythmites in Madre de Dios, Peru

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ABSTRACT

New data from upper Miocene deposits in the Madre de Dios region, southern Peru, allow the delineation of tidal regime for the first time in western Amazonia and provide strong evidence of elevated tidal range and brackish-water influence. The results point out the insufficiency of the current depositional models and support the earlier hypothesis that western Amazonia was also connected to the Paranan Sea during the late Miocene. In this paper we present sedimentological, ichnological, and statistical (Fourier transformation) data from two selected outcrops containing rhythmite successions from an area that is traditionally considered as continental. The sediments are interpreted to represent tide-dominated, inner-middle estuarine deposits. The cyclic rhythmites display semidiurnal cyclicity. The results are significant because (1) they contradict recent interpretations of the area's paleoenvironmental history; (2) the evidence for tidal processes is persuasive; and (3) the delineated tidal regime and range provide a unique insight into the depositional dynamics of a system having many important paleogeographic implications.

Keywords: sedimentology, ichnology, tidal deposits, western Amazonia, Miocene.

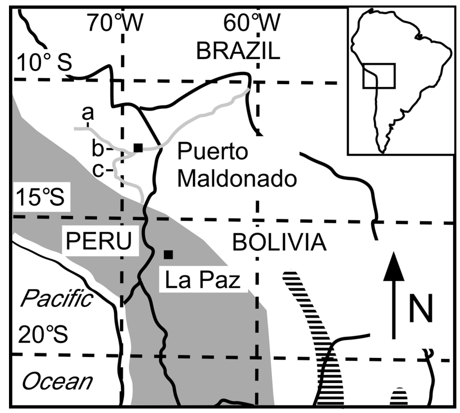

Figure 1. Study locations: (a) Manu River, Cocha Cashu (two sections—11.90318°S, 71.39417°W and 11.89661°S, 71.42533°W); (b) Madre de Dios River, Cerro Colorado (12.56787°S, 70.10265°W); (c) Inambari River (12.92209°S, 70.34911°W). Horizontally ruled areas in southern part of map indicate known extent of Paranan Sea (after Marshall et al., 1993). Gray shading—Andes.

INTRODUCTION

The Miocene depositional history in the western Amazonia foreland basin is complex, and there are controversial views about the area's paleoenvironmental history and especially about possible marine incursions. Several studies have suggested tidal influence and marginal-marine affinity in the area (e.g., Hoorn, 1993; Räsänen et al., 1995; Gingras et al., 2002, and references therein). However, these interpretations are questioned by numerous authors, who have favored seasonal energy fluctuations (e.g., Hoorn, 1996), or a microtidal lake setting (Wesselingh et al., 2002; Vonhof et al., 2003) as a more plausible explanation for the presence of tidal or ''pseudo'' tidal deposits. The objective of the study is to provide new data concerning the controversy. For this purpose, two selected outcrops containing continuous series of rhythmic deposits were sedimentologically, ichnologically, and statistically (Fourier transformation) studied in the Madre de Dios region, southern Peru. The outcrops are 200 km south of the southernmost described marginal-marine occurrence of the northward-extending embayment (Gingras et al., 2002). The results show evidence of cyclic tidal rhythmites within a marginal-marine setting and allow the delineation of the ancient tidal regime for the first time in Miocene western Amazonia. They point out the insufficiency of the current depositional models and support the earlier (restricted) seaway hypothesis for late Miocene time.

STUDY LOCATIONS

The locations studied are situated along the Madre de Dios River (Cerro Colorado) and the Manu River (Cocha Cashu) (Fig. 1). The data are complemented by observations from one other location in the area (Inambari River). Stratigraphically, the sediments belong to the Ipururo and Madre de Dios Formations (Kummel, 1948; Oppenheim, 1946, respectively), which are known as the Solimões Formation in Brazil. Cerro Colorado is above a regional unconformity, whereas Cocha Cashu is below it. An articulated proboscidean fossil was discovered in the Cerro Colorado outcrop (Campbell et al., 2000). The age of the deposits is estimated as ca. 9 Ma on the basis of $^{40}Ar/^{39}Ar$ dates (Campbell et al., 2001).

MATERIALS AND METHODS

The basic data set consists of sedimentological and ichnological field descriptions. Grain size, sedimentary structures, paleocurrent directions (measured from ripple and dune foresets), nature of bedding, and bedding contacts were described. The sedimentological approach also includes analysis of rhythmite-thickness data. The thickness variations of the sand-clay or silt-clay couplets (a couplet is defined as a sand or silt lamina and the bounding upper clay lamina) were measured from one dune foreset succession ($n = 237$, from Cocha Cashu) and from one vertically accreted rhythmite succession ($n = 242$, from Cerro Colorado) (Figs. 2A, 2C, respectively). These data were analyzed by the spectral procedure of SAS 8.2 (finite Fourier transform) to detect possible cyclicities. Thicknesses of the adjacent (couplets 1 and 2, 3 and 4, . . .) and every third couplet (couplets 1 and 3, 2 and 4, 5 and 7, . . .) were also compared manually (Figs. 3A, 3C). There are two possible sources of error: (1) in places (especially in Cerro Colorado) there are signs of erosion in some mud drapes and (2) the mud drapes are not always well developed (thin, discontinuous). The locally poor preservation and imperfect lamina

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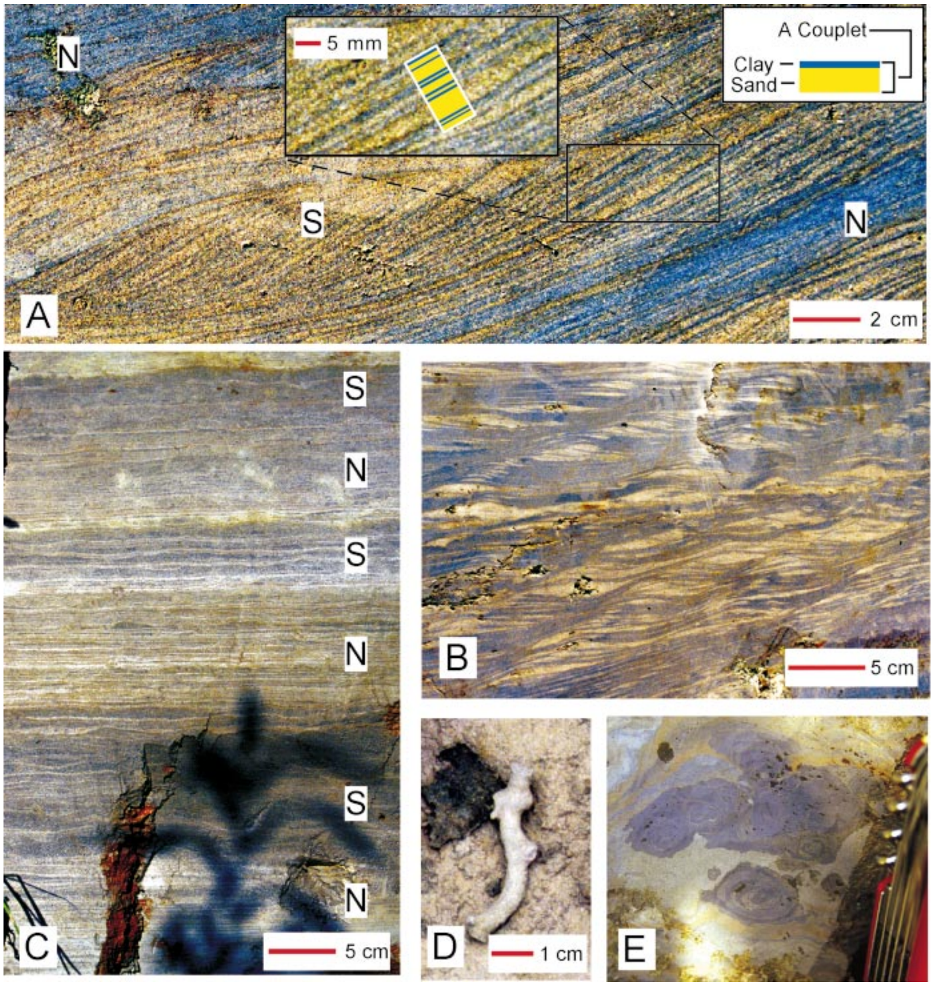

Figure 2. A: Heterolithic cross-stratification forming cyclic rhythmites from Cocha Cashu (see Figs. 3A, 3B). S and N refer to interpreted presence of spring and neap tides, respectively, based on data in Figure 3A. B: Climbing-ripple bedding from Cocha Cashu. C: Vertically stacked silt-clay couplets displaying cyclic rhythmites from Cerro Colorado (see Figs. 3C, 3D). N and S labeling is based on data in Figure 3C. D: *Thalassinoides* from second location in Cocha Cashu. E: *Asterosoma* from Inambari River. Knife for scale.

development may hinder recognition of individual clay drapes, leading to amalgamation of a few couplets.

The ichnological approach included documentation of genera, size of the traces, and bioturbation intensity.

RESULTS

Facies

At the Cerro Colorado site, the deposits consist of a 40-m-thick succession of 3 stacked, 10–16-m-thick, upward-fining successions (Fig. DR1[1]). Their lower contacts are sharp and commonly bear mud clasts. The lower parts of the successions consist of unlithified, massive or trough cross-stratified, well-sorted, fine- to medium-grained sand deposits. Upward, the deposits grade into current-rippled, fine-grained sand or heterolithic climbing ripples, and then into intercalated, horizontal sand and mud beds (Fig. 2C). In the uppermost succession, these beds are inclined, forming inclined heterolithic stratification (IHS of Thomas et al., 1987). The thickness of sand and mud beds ranges roughly from 20 cm to 0.5 cm, and internally the thicker beds comprise cosets of heterolithic ripples or horizontal undulation. The contact from sand to mud is commonly gradational, whereas the contact from mud to sand is abrupt. The paleocurrents show dominantly northeast orientation. The bioturbation intensity is generally low (absent), but locally in the upper part of the succession, dense, low-diversity assemblages occur at the finer-grained interbeds. The genera observed include *Planolites* (common, 1–3 mm in diameter), *Palaeophycus* (locally common, 4–6 mm), and *Ophiomorpha* (rare, 10–15 mm). Dense, monospecific assemblages of *Taenidium* (5 mm) are locally present.

The upward-fining successions are capped by up to 2-m-thick pedogenic, sandy clay intervals. The whole succession is bounded by an erosional surface with conglomerates in the top.

At Cocha Cashu, the outcrop studied is ~10 m thick, and laterally it can be followed for ~100 m. The facies consist of bluish, mud-dominated inclined heterolithic stratification forming sharp-based, upward-fining successions as much as 3 m thick (Fig. DR2; see footnote 1). The successions begin with massive or cross-stratified, fine-grained sand, commonly with mud clasts. Upward, the deposits turn into clay-draped, climbing-ripple–bearing sand and silt (Fig. 2B) or into clay-draped ripple or two-dimensional dune cross-stratified sand or silt (Fig. 2A). As cosets, they form flaserlenticular bedding and have a low ($<10°$) depositional dip. The top of the successions commonly consists of interlaminated silt and clay. Soft-sediment deformation is common. The paleocurrent directions are dominantly toward the east and west. Bioturbation is generally absent, but where present, the trace-fossil genera observed include bedding-plane traces such as *Diplichnites*, *Undichna*, and *?Phycodes*. Near the top of the outcrop, a low-density assemblage of *Taenidium* is observed. The contact with the overlying deposits is not seen in detail, but the sediments overlying the contact (studied at the second-listed location at Cocha Cashu, Fig. 1) consist of the same succession as in Cerro Colorado. The trace fossil fabric consists of reburrowed (by *Planolites*) *Ophiomorpha* (common, different sizes, up to 4 cm in diameter), *Thalassinoides* (common, 3–6 mm in diameter) (Fig. 2D), and *Gyrolithes* (moderate, 3–6 mm). In another location in the area (along the Rio Inambari; see Fig. 1), an *Asterosoma* (5–20 mm in diameter) fabric was described (Fig. 2E).

Fourier Analysis and Thick-Thin Alternation

The white noise test indicates a nonrandom origin for both rhythmite successions. In spectral-density plots, the most prominent peak occurs at frequency 0.106, indicating a period of 59.3 couplets for Cocha Cashu (Fig. 3B); minor peaks occur at 21.5 and 2.09 couplets. In Cerro Colorado, the highest spectral-density values occur at the 120.5, 60.25, and 30.125 couplets (Fig. 3D). A minor peak takes place at the 2.36 couplets. In both the diagrams, frequencies 0–0.05 were not included.

The manual examination of the adjacent and every third couplets shows thick-thin al-

[1]GSA Data Repository item 2005033, Figures DR1 and DR2, summary of data from outcrops, is available online at www.geosociety.org/pubs/ft2005.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

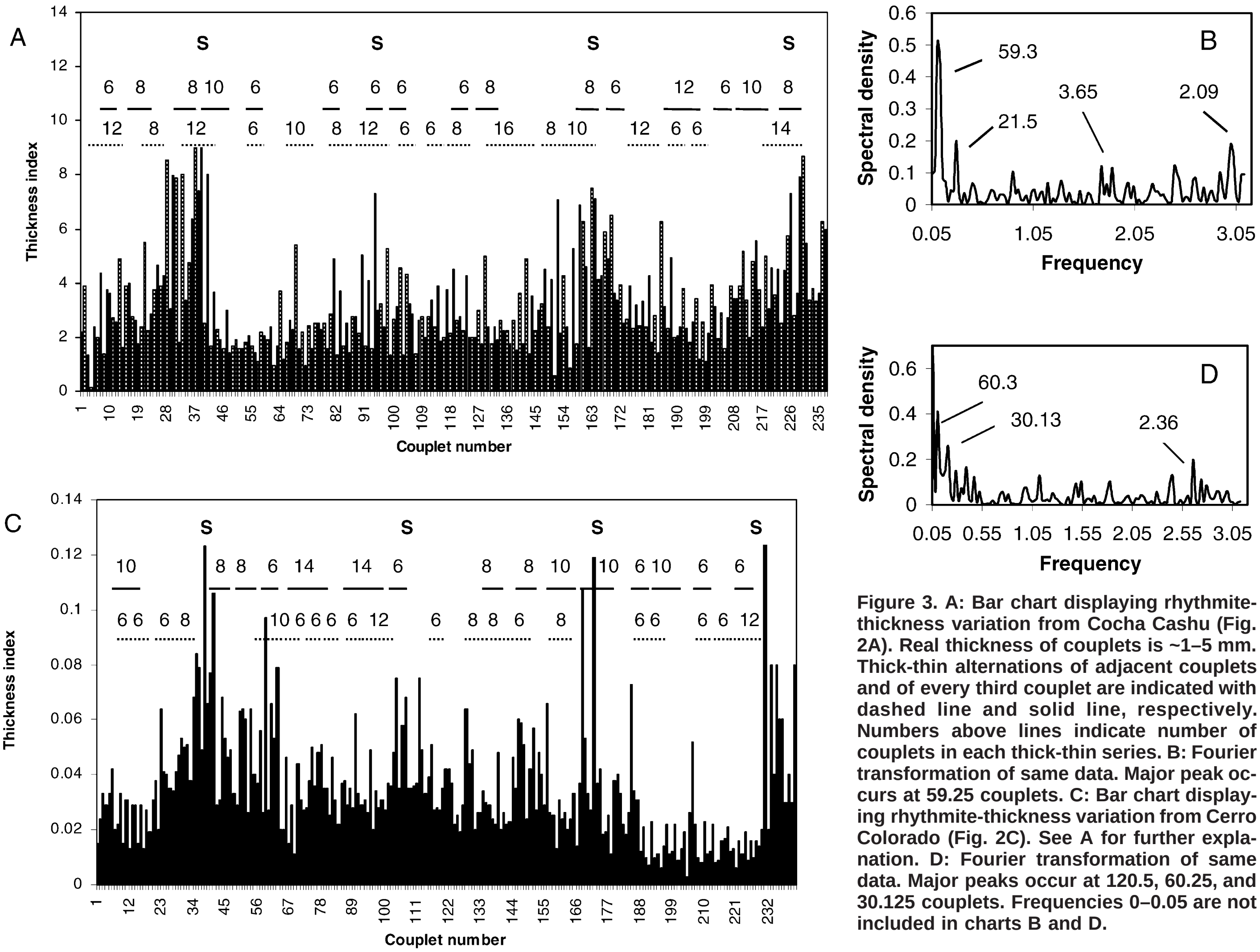

Figure 3. A: Bar chart displaying rhythmite-thickness variation from Cocha Cashu (Fig. 2A). Real thickness of couplets is ~1–5 mm. Thick-thin alternations of adjacent couplets and of every third couplet are indicated with dashed line and solid line, respectively. Numbers above lines indicate number of couplets in each thick-thin series. B: Fourier transformation of same data. Major peak occurs at 59.25 couplets. C: Bar chart displaying rhythmite-thickness variation from Cerro Colorado (Fig. 2C). See A for further explanation. D: Fourier transformation of same data. Major peaks occur at 120.5, 60.25, and 30.125 couplets. Frequencies 0–0.05 are not included in charts B and D.

ternation in several series, up to 16 and 14 couplets long, respectively (Figs. 3A, 3C).

INTERPRETATION

Depositional Environments

The deposits in Cerro Colorado and Cocha Cashu are interpreted to display tidal deposition in laterally accreting channels, intercalated with continental environments. In both locations, the features indicating tidal affinity include (1) bipolar paleocurrents, (2) frequent reactivation surfaces, (3) sedimentary couplets and double mud drapes, and (4) cyclic thickness variation of sedimentary couplets (Figs. 2A, 2C) (e.g., Nio and Yang, 1991). The deposits are mainly considered as subtidal because of the interpreted presence of both flood and ebb couplets (double drapes).

The facies were further interpreted to display mainly inner-estuarine subenvironments because of (1) often unbioturbated, well-developed tidal rhythmites (Kvale and Mastalerz, 1998); (2) very common presence of heterolithic climbing ripples in inclined heterolithic stratification (Lanier and Tessier, 1998); and (3) the type of ichnofabrics, where present. The latter are composed mainly of low-diversity assemblages of feeding burrows of trophic generalists (cf. Pemberton and Wightman, 1992), monospecific assemblages of meniscus-bearing burrows, or assemblages of bedding-plane trackways (cf. Buatois et al., 1997). In concert, the sedimentological and ichnological factors point to a proximal turbidity maximum at the fluvial-tidal transition (cf. also Archer and Hubbard, 2003). In addition, the upper part of the Cerro Colorado outcrop and especially the overlying deposits at the Cocha Cashu outcrop display a clearer brackish-water (?mesohaline) trace-fossil fabric (*Ophiomorpha*, *Thalassinoides* [Fig. 2D], and *Gyrolithes*). These trace-fossil data further suggest transgression for the Cerro Colorado sediments and a shift toward middle-estuarine deposition. The character of the relative sea-level change is not clear in Cocha Cashu; therefore a deltaic setting is also possible. The *Asterosoma* ichnofabric (Fig. 2E), commonly found in normal-marine conditions, is also consistent with a marginal-marine setting.

Rhythmites and Tidal Regime

The results of the Fourier analysis (and visual observation) indicate a prominent cyclicity of 59.3 and 60.3 couplets (Figs. 3B, 3D). This cycle is interpreted to correspond to the semimonthly spring tides in four-element rhythmites (cf. Archer et al., 1995; Archer, 1998), because of the following observations. In addition to the regular thick-thin alternation of successive couplets as observed manually, comparison of every third couplet shows a strong inequality (Figs. 3A, 3C). De Boer et al. (1989) evaluated the significance of thick-thin bundle alternation series in proving tidal influence. Even though their model was intended for cycles briefer than 30 couplets, a reasonable comparison can be made; the likelihood of a nonrandom origin for the thick-thin alternation of every third couplet is very high (>90%) (e.g., see the series of 14 and 14 couplets in Fig. 3C) in these sediments. Therefore, the adjacent thick-thin paring and the thick-thin alternation of every third couplet are most likely related to the flood-ebb deposition and the diurnal inequality, respectively (cf. Archer et al., 1995). The interpretation of having deposition during both flood and ebb currents is also supported by bipolar paleocurrents. The cyclicity of 59.3 couplets would therefore indicate 29.5 ordinate currents in a cycle, closely resembling the semidiurnal deposition during a synodic half-month.

The presence of cyclic rhythmites may further indicate an elevated (at least mesotidal) tidal range (Archer, 1998)

IMPLICATION FOR THE DEPOSITIONAL SYSTEM

The results contradict the interpretations (1) of these deposits as fluvial (Campbell et al., 2000) and (2) that there were no marine incursions in western Amazonia after the late-middle Miocene (Tortonian) sea-level fall (Hoorn, 1996). The presence of a semidiurnal regime poses further important constraints for the system's paleogeography. The only commonly accepted sea connection of the system until the middle Miocene was through the Caribbean Sea, >2500 km to the north of the study locations. Semidiurnal inequality results from influence of higher latitudes in this kind of equatorial system (De Boer et al., 1989) and requires a 12 h resonance time from the embayment. Therefore, the epicontinental bay in between should have had a considerable depth, with an open sea connection (cf. Archer et al., 1994). This scenario is unlikely owing to the late Miocene uplift in the northeastern Andes and the consequent change in the Caribbean connection (Hoorn et al., 1995). In addition, the fossil data do not support open-marine conditions in central-western Amazonia during that time (e.g., Lundberg et al., 1998). An alternative more plausible explanation (based on foraminiferal data) is that the depositional system had a connection to the contemporary Paranan Seaway (Fig. 1) through Bolivia (e.g., see Marshall et al., 1993), as suggested by some authors (e.g., see Boltovskoy, 1991, and references therein). The ingression was likely related to the accelerated tectonic subsidence in the central Andean foreland subbasins that began at 11 Ma (Marshall and Lundberg, 1996).

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