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Tidal rhythmites in the southern Bouse Formation as evidence for post-Miocene uplift of the lower Colorado River corridor

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ABSTRACT

Uncertainty over depositional paleoenvironments of the upper Miocene to lower Pliocene Bouse Formation obscures our understanding of the timing and magnitude of regional uplift as well as the conditions and processes that were active during integration and early evolution of the Colorado River (western United States). This paper presents new sedimentologic and quantitative evidence for a strong tidal influence on deposition of the basal carbonate member of the southern Bouse Formation. Lithofacies with tidal sedimentary structures include lime mudstone with reed and grass imprints; heterolithic facies with horizontal, flaser, wavy, and lenticular bedding; and cross-bedded grainstone with sigmoidal bundles, reactivation surfaces, and complex bedding. Systematic alternation of relatively thick and thin layers records a predominantly semidiurnal mixed-tidal depositional environment, and Fourier analysis highlights the cyclic, non-random nature of layer-thickness trends. These observations provide evidence that the southern Bouse Formation accumulated in a pre–Colorado River tide-dominated marine setting at the north end of the Gulf of California. Deposition at sea level requires ~330 m of uplift in the lower Colorado River and western Colorado Plateau region during the past ~5.0 m.y.

INTRODUCTION

Our understanding of the conditions and processes that were active during integration and early evolution of the Colorado River (western United States), as well as models for post-Miocene tectonic uplift of the western Colorado Plateau region, depend on interpretation of depositional environments of the uppermost Miocene to lower Pliocene Bouse Formation (Fig. 1). The southern Bouse Formation is interpreted to have formed in either a marginal-marine setting at the north end of the late Miocene Gulf of California oblique rift, as suggested by marine and brackish-water fossils and sedimentary structures (Buising, 1990; Turak, 2000; McDougall, 2008; McDougall and Martínez, 2014), or a large inland lake isolated from the ocean, as suggested by Sr isotopes, stable isotopes, and elevation data (Spencer and Patchett, 1997; House et al., 2008; Spencer, et al., 2008, 2013; Bright et al., 2016). The isolated-lake hypothesis explains the presence of marine fossils by introduction of marine organisms by birds.

Although Sr isotopes have been used to suggest a lacustrine origin for the Bouse Formation, a recent modeling study shows that the observed Sr-isotope values could have resulted from mixing of marine-water, freshwater, and radiogenic spring-water components (Crossey et al., 2015). Thus Sr values slightly more radiogenic than seawater do not preclude a marine influence. Deposition of the southern Bouse Formation at sea level would require ~330 m of post-depositional tectonic uplift in the western Colorado Plateau region to explain the modern elevations of known outcrops, whereas accumulation in an isolated lake would place no constraint on post-Miocene uplift.

In this paper, we present new sedimentologic and layer-thickness data to interpret the depositional paleoenvironment of the southern Bouse Formation. We focus on the basal carbonate member of the Bouse Formation exposed south of Blythe, California (Fig. 1), a mixed carbonate-siliciclastic unit that rests on Miocene conglomerate and volcanic rocks (Fig. 2A). Sedimentary lithofacies and quantitative analyses presented below provide new evidence for deposition under the influence of tidal currents, consistent with a well-documented marine to brackish-water fauna in the southern Bouse Formation.

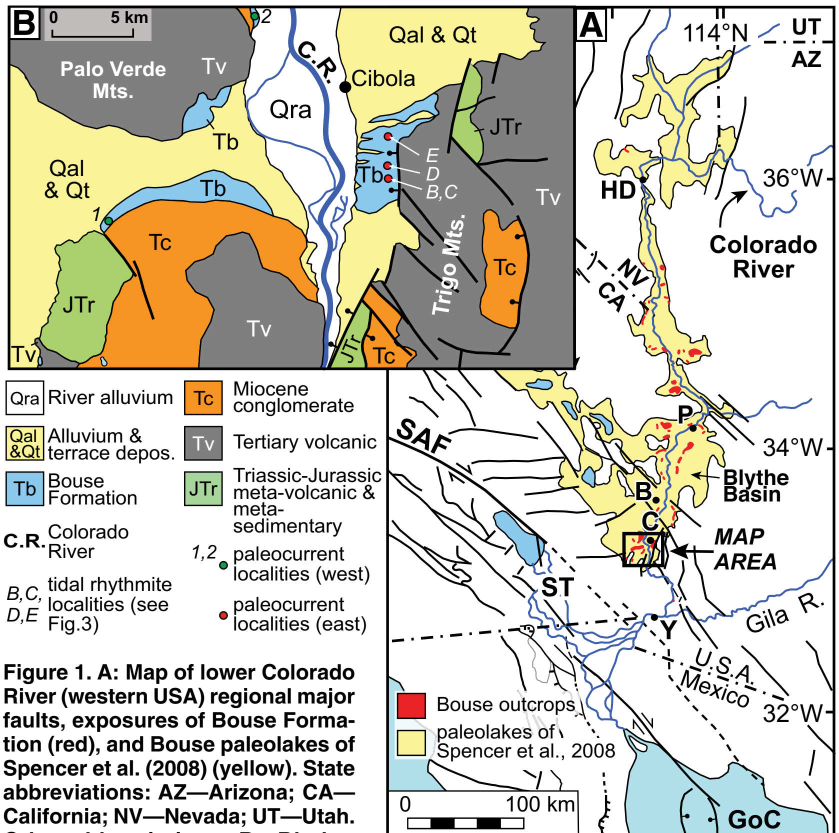

Figure 1. A: Map of lower Colorado River (western USA) regional major faults, exposures of Bouse Formation (red), and Bouse paleolakes of Spencer et al. (2008) (yellow). State abbreviations: AZ—Arizona; CA—California; NV—Nevada; UT—Utah. Other abbreviations: B—Blythe; C—Cibola; GoC—Gulf of California; HD—Hoover Dam; P—Parker; SAF—San Andreas fault; ST—Salton Trough; Y—Yuma. B: Simplified geologic map of study area, compiled from Sherrod and Tosdal (1991). depos.—deposits.

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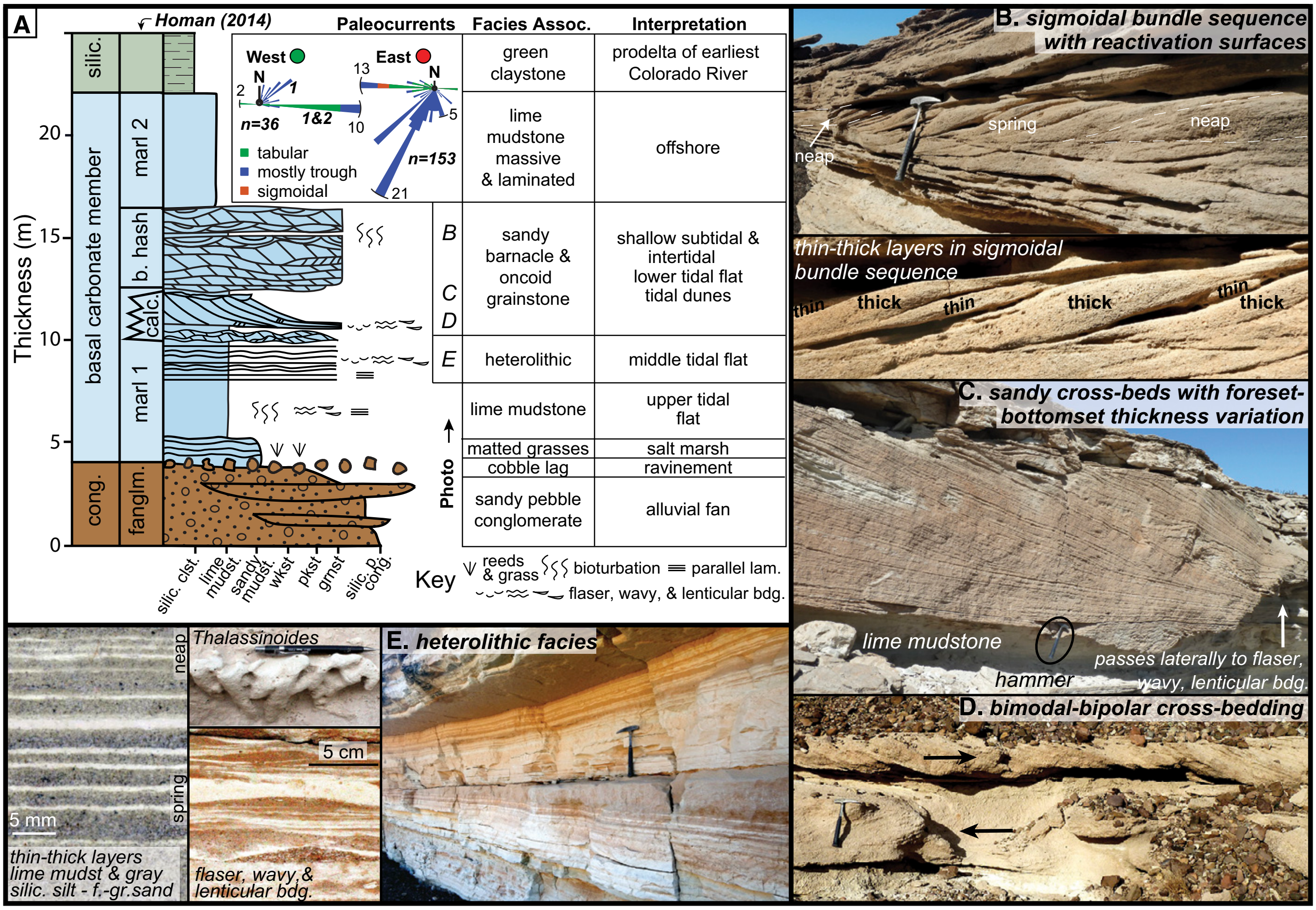

Figure 2. A: Representative stratigraphy of southern Bouse Formation (western USA) after Homan (2014), sedimentary lithofacies examined in this study, and environmental interpretations. Paleocurrent locations are shown in Figure 1B. B: Sigmoidal bundle sequence with reactivation surfaces and thin-thick couplets. C: Cross-bedded grainstone passing laterally into flat bottomsets to flaser, wavy, and lenticular bedding. D: Bimodal-bipolar cross-bedding in bioclastic grainstone. E: Heterolithic facies with *Thalassinoides* burrows, horizontal couplets, and flaser, wavy, and lenticular bedding. Pencil is 14 cm; hammer is 32.5 cm. Abbreviations: silic.—siliciclastic; clst.—claystone; mudst.—mudstone; wkst.—wackestone; pkst.—packstone; grnst.—grainstone; p. cong.—pebble conglomerate; b. hash—barnacle hash; calc.—calcarenite; fanglm.—fanglomerate; bdg.—bedding; lam.—lamination; f.-gr.—fine-grained.

RESULTS

Sedimentary Lithofacies

The basal carbonate member of the southern Bouse Formation includes: matted silty lime mudstone with reed and grass imprints; heterolithic facies comprising wackestone, grainstone, and bioturbated lime mudstone with horizontal, flaser, wavy, and lenticular bedding; and cross-bedded barnacle-oncoid grainstone. These lithofacies contain sedimentary structures that are commonly attributed to a tidal origin, including (Fig. 2): (1) well-sorted and segregated carbonate-siliciclastic couplets that display systematic alternation of thin and thick millimeter- to centimeter-scale layers; (2) distinctive sigmoidal bundles; (3) cross-bed foresets that pass laterally into stacked wavy, lenticular, and flaser heterolithic bedding; (4) lateral variations in thickness of cross-bed and sigmoidal bundle foresets and bottomsets; (5) common reactivation surfaces; (6) cross-lamination that records reversing currents and migration of ripples up meter-scale foresets; (7) *Thalassinoides* burrows; and (8) bimodal-bipolar cross-bedding (e.g., Nio and Yang, 1991; Longhitano et al., 2012; Davis, 2012). Lime mud is a common component of these deposits and is ubiquitous in other carbonate depositional systems.

Lateral and vertical transitions and complex interbedding geometries are abundant in the southern Bouse basal carbonate. For example, foreset strata of cross-bedded barnacle-oncoid grainstone pass laterally into flat-lying bottomsets of well-sorted sandy grainstone with small-scale bimodal-bipolar ripples, reactivation surfaces, and lime mud drapes, which pass laterally into stacked flaser, wavy, and lenticular bedding of the heterolithic facies association.

Layer-Thickness Analysis

Layer-thickness and Fourier analyses of rhythmites are used extensively to test for and establish a tidal influence on sedimentation (e.g., Kvale et al., 1999; Williams, 1989; Hovikoski et al., 2005). The most distinctive sequences form in mixed diurnal and semidiurnal tidal systems where the semidiurnal signal is relatively strong (De Boer et al., 1989; Williams, 2000). This type of tidal environment creates systematic alternation of thick and thin layers where each couplet is deposited in one tidal cycle. Preservation of daily couplets is enhanced by hydraulic sorting and segregation in mixed bioclastic-siliciclastic tidal systems (Longhitano, 2011). Where a layering sequence is nearly complete, Fourier analysis reveals daily to monthly cyclicity. Rhythmite sequences commonly are incomplete due to the influence of non-tidal processes such as storms, waves, and partial submergence or emergence of tidal flats (e.g., Kvale et al., 1995). Deposition of tidal rhythmites typically is dominated by short-term very fast accumulation rates.

Data for modern tides from the northern Gulf of California express a semi-diurnal oscillation superposed on the monthly spring-neap tidal cycle (Fig. 3A) and are used for comparison to the southern Bouse Formation rhythmite layers. Bouse rhythmites analyzed for this study include laminae, thin beds, and thin-thick couplets in horizontal layers, sigmoidal bundles, and cross-bed foresets. Fourier transformed layer-thickness series show well-defined peaks at 0.96 and 1.91 cycles/couplet (Fig. 3B), similar to the Fourier components of modern tides in the northern Gulf of California which display weighted-average diurnal and semidiurnal frequencies at 0.92 and 1.92 cycles/day (Fig. 3A). This bimodal signal is characteristic of a dominantly semidiurnal mixed-tidal marine setting (De Boer et al., 1989; Archer and Johnson, 1997; Williams, 2000). Apparent neap-spring long-wavelength tidal cyclicity is present in thickness series of horizontal rhythmites, cross-bed foresets, and sigmoidal bundle sequences with prominent fast Fourier transform (FFT) peaks at periods of 4–10 couplets/cycle (8–20 layers/cycle) (Figs. 3C–3E), as is commonly seen in tidal-flat sequences (Kvale et al., 1995). We interpret segregation of siliciclastic and bioclastic sediment to record hydraulic sorting due to regular changes in tidal current energy and contrasting entrainment potential of the two grain types (e.g., Longhitano, 2011).

DISCUSSION AND CONCLUSIONS

We find that the basal carbonate member of the southern Bouse Formation was deposited in a tide-dominated marginal-marine setting based on: (1) Fourier analysis of rhythmite successions that record daily and neap-spring tidal cyclicity; (2) remarkable continuity, sorting, and lithological segregation of thin-thick couplets; (3) distinctive sigmoidal bundle sequences and non-random tidal bundling; and (4) abundance and variety of tidal sedimentary structures, lateral relationships, and vertically stacked tidal facies assemblages (e.g., Dalrymple, 2010). Our data and interpretation are in agreement with a moderately diverse marine to brackish-water faunal assemblage documented from south of Blythe, California, to Parker, Arizona (Fig. 1; McDougall, 2008; McDougall and Martínez, 2014). Collectively, these new observations and existing paleontology are best explained by deposition in a marine tidal environment.

Long series of thin-thick layer alternations (Figs. 3B–3D), and apparent neap-spring cyclicity in heterolithic and grainstone facies (Figs. 3C–3E), are predicted for a mixed-tidal marine setting and are inconsistent with deposition in an isolated lake. While some of the observed sedimentary structures are found uncommonly in non-tidal environments, deposition in a lake would produce non-cyclic layering due to random variations in flow velocity and direction (Ainsworth et al., 2012). The cyclic periodic thickness variations and regular lithologic alternations in the southern Bouse Formation are not formed by non-tidal processes such as tributary river floods, storms, wind-generated lake currents, or biochemical varve deposition (Ainsworth et al., 2012; Dalrymple and Choi,

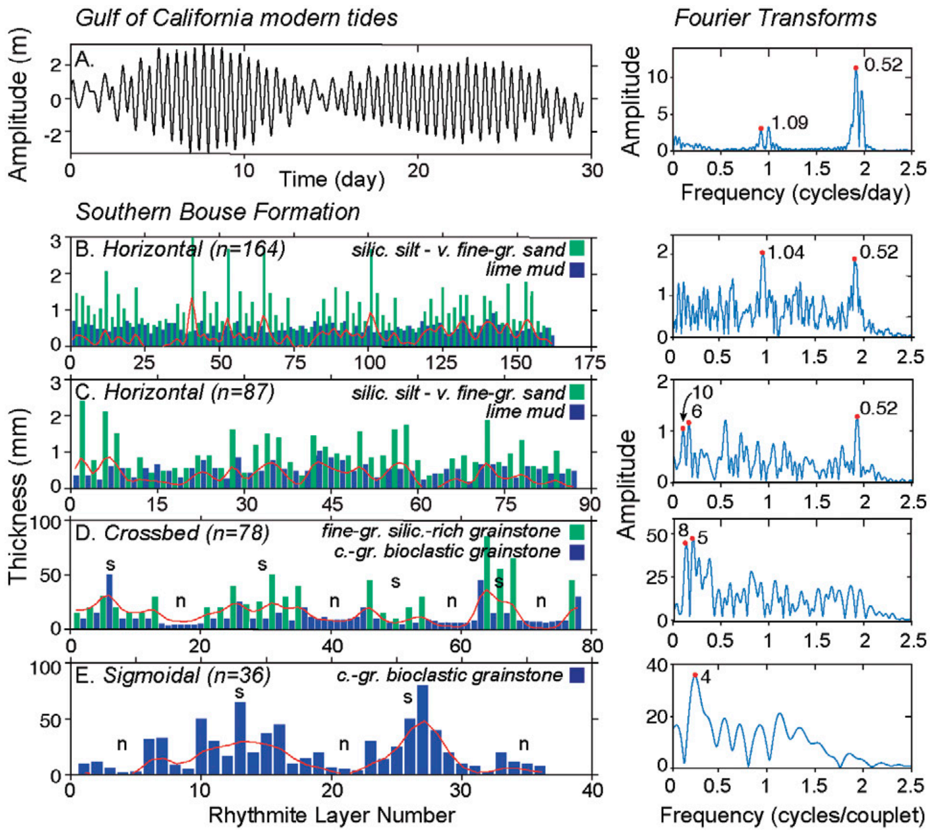

Figure 3. A: One month (March 1993) of modern tide record at San Felipe, northern Gulf of California (http://sanfelipe.com.mx/weather/tide-calendars) and fast Fourier transform (FFT). Note strong semidiurnal signal with two cycles per day, and longer-wavelength oscillating constructive-destructive interference between solar and lunar tides. Red dots and corresponding numbers indicate period (days per cycle). B–E: Layer-thickness data and FFTs for southern Bouse Formation rhythmites. Red curve superimposed on rhythmite data indicates a five-point moving average (1, 4, 6, 4, 1). Red dots and corresponding numbers indicate period (couplets per cycle). B: Horizontal lamina with clear thin-thick alternations of lime mudstone (blue) and siliciclastic (silic.) silt to very fine-grained (v. fine-gr.) sand (green). FFT has strong peaks at frequencies of 0.96 and 1.91 cycles/couplet. C: Another example with strong peak at 1.92 cycles/couplet. Neap-spring cyclicity is inferred from low-frequency peaks with periods (inverse of frequency) at 10 and 6 couplets/cycle. D: Cross-bedded grainstone showing strong alternation sequence during inferred spring tides (s) but no alternation during inferred neap tides (n) with strong peaks at period of 8 and 5 couplets/cycle (c.-gr.)—coarse-grained. E: Sigmoidal rhythmites with peak at 4 couplets/cycle. See the GSA Data Repository[1] for FFT methods.

[1]GSA Data Repository item 2017025, rhythmite thickness data, methods, and Matlab code, is available online at http://www.geosociety.org/pubs/ft2017.htm or on request from editing@geosociety.org.

2007; De Boer et al., 1989). Tidal sedimentary structures are generally preserved only in macrotidal, mesotidal, or highly microtidal settings with a strong asymmetry between daily high and low tides (Archer, 1998). Proposed modern analogues for the Bouse isolated-lake model, such as the Great Lakes, Black Sea, and Caspian Sea, are essentially non-tidal (Eisma et al., 1998; Fraser et al., 1991) and could not produce the rich assortment of tidal facies with cyclicity documented in this study. These results show that the southern Bouse Formation accumulated in a marine embayment at the north end of the Gulf of California with a mixed-tidal regime similar to that of the modern Gulf of California. Consistent basinward dips of foreset strata (Fig. 2A) indicate that bedform migration and deposition were dominated by ebb-tide currents.

During the past ~20 yr, radiogenic (Sr; e.g., Spencer and Patchett, 1997) and stable isotopes (C, O; e.g., Bright et al., 2016) have played a major role in interpretation of the Bouse Formation. Importantly, however, these data sets could be influenced by mixing of river and marine waters with radiogenic spring waters (Crossey et al., 2015) or by post-depositional alteration resulting in open-system isotopic behavior (Crow et al., 2016). This concern is particularly relevant for carbonate material where poorly buffered trace-metal systems such as Sr are commonly altered by diagenesis and other post-depositional influences (e.g., Brand and Veizer, 1980). These complexities require an integrated petrographic-geochemical approach and careful sample screening for trace metal–based carbonate geochemistry (Hood et al., 2016). Process sedimentology and the quantitative analyses presented here provide unique insights into physical processes that are not subject to the concerns and ambiguities of potential post-depositional alteration.

Our conclusion of a tide-influenced marine setting for the southern Bouse Formation supports significant post-Miocene uplift in the western Colorado Plateau region (e.g., Karlstrom et al., 2012; Crow et al., 2014) and suggests activity of young (post-subduction) crustal and upper-mantle deformation processes that remain incompletely understood.

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