Depositional paleoenvironments of the basal carbonate member of the southern Bouse Formation, Cibola, Arizona

Brennan O'Connell and Rebecca J. Dorsey
Dept. of Geological Sciences, University of Oregon, Eugene, Oregon, 97403

ABSTRACT—Detailed sedimentological analysis of the late Miocene to early Pliocene Bouse Formation south of Blythe, CA, provides insights into depositional processes and allows reconstruction of ancient depositional environments. The southern Bouse Formation is a succession of mixed carbonate and siliciclastic sediment overlain by a siliciclastic deltaic sequence of Colorado River sediment, capped by a recently discovered widespread upper bioclastic limestone unit (Homan, 2014; Dorsey et al., this volume). The basal carbonate member of the southern Bouse Formation contains a complex mosaic of mixed carbonate and siliciclastic deposits that reveal lateral facies changes and a stacked vertical succession consisting of: nearshore gravels, calcareous sandstone and calcarenite, mid-platform lagoonal to tidal flat marl, tidal bars, platform-margin grainstone sandy shoals, and offshore micrite (marl). The Bouse Formation records a major transgression in the Blythe basin, which has been variably interpreted as a marine estuary or a saline lake isolated from the ocean. Sedimentary structures characteristic of tidal processes and environments are common in the low-energy lagoonal and tidal-flat marl, and high-energy tidal bar facies associations, providing evidence for a strong tidal influence on deposition of the Bouse basal carbonate. As such, we favor a marginal-marine interpretation for the Bouse basal member. We believe the alternative interpretation—that lake currents produced all of these features—cannot account for either the high abundance of tidal sedimentary structures or the systematic lateral and vertical distribution of lithofacies that is commonly observed in tidally-influenced transgressive coastal to nearshore depositional systems.

Facies associations and process interpretations

(1) Ravinemet Association

Facies A—Basal Cobble Lag: Well-sorted volcaniclastic cobble lag, overlies the Miocene fan conglomerate "fanglomerate", and underlies mixed carbonate and siliciclastic facies of the Bouse basal carbonate member.

Process Interpretation: transgressive ravinement surface—currents associated with initial transgression winnowed and removed finer sediment, concentrating cobble clasts on the surface.

(2) Nearshore Association

Facies B—Golden Gravel: Golden brown to gray green, rounded to sub-rounded, typically well-sorted, coarse sandstone to pebble conglomerate. Exhibits tabular cross stratification with cross-bed sets 0.5–3 meters, and primary dips ranging from nearly horizontal to steep forests (~20–30°). Both normally graded and ungraded sandstone beds are characteristic features of this lithofacies, with upslope and downslope variations of grain size in foresets. Clasts are dominated by granitic and intermediate plutonic, volcanic breccia, and unwelded tuff lithologies. Matrix is mixed carbonate and siliciclastic sand. This facies is often discontinuous laterally, exhibiting strongly lenticular geometry. Locally, within the dirty calcarenite and calcareous sandstone (facies C) of the nearshore association, golden gravel granules to pebbles are found as distinct thin beds, 1–3 granule to small pebble grains thick, extending laterally from lenticular crossbedded gravel.

Process Interpretation: locally sourced, wave worked beach gravels, gilbert delta lobes, high-energy bedforms, and detached nearshore gravel bars. Pebble beds likely were transported by high energy storm currents, and some transport may have been affected by tidal currents.

Facies C—Sandy calcarenite and calcarenitic sandstone: White to gray, pale green, and light tan, well-rounded to subrounded, moderately to well-sorted, fine-to-medium grained, laminated to thick-bedded, admixed carbonate and siliciclastic calcareous sandstone and sandy calcarenite (Note: in this context, "sand" refers to the siliciclastic sand-size grains). Siliciclastic component ranges from >10% to 70% of the siliciclastic–carbonate mixture. Internal sedimentary structures are often well preserved, and include asymmetrical and symmetrical ripple cross lamination, trough and tabular cross-bed sets, and parallel lamination overlain by asymmetrical ripples. This unit is interbedded with the low-energy, lagoonal and tidal flat association as continuous, distinct thin beds of dirty calcarenite with sharp bases and asymmetrical rippled tops. *Thalassinoides* burrows in this facies locally are observed to pass laterally into continuous bioturbated beds of Facies E of the Low Energy Lagoonal and Tidal Flat Association.

Process Interpretation: proximal bottomsets of gilbert deltas and gravelly bars of the Golden Gravel (facies B) nearshore facies association. Facies C formed adjacent to both the golden gravel of the nearshore association, and lagoonal and tidal flat marl association.

(3) Low Energy, Lagoonal and Tidal Flat Association:

Facies D –Heterolithic, interbedded silty carbonate clay and marl: White, gray, to light pink, includes mm–cm scale laminations to very thin beds that alternate between lime mudstone and mm laminations of either white micrite or pale green siliciclastic clay. Weathers platey, with pinch and swell along bedding planes. High silica content, concoidal weathering pattern.

Facies E—Mudcracked, heterolithic, lime mudstone with silt–f.g. bundles of laminations, wavy, flaser, and lenticular beds. A few distinct beds with abundant *Thalassinoides* burrows are present in this facies (trace fossil I.D. by S. Hasiotis, personal communication). Rhythmites of v.f.g sand and carbonate mud contain abundant stacked, wavy, lenticular and flaser bedding in a well-sorted and segregated silt and clay that display mm– to cm–scale alternations with lime mud. The stacked flaser, wavy, and lenticular bedding is consistently overlain by Platform Margin Association in vertical stratigraphic sequence, and passes laterally into grainstone bars of the high-energy tidal bar association.

Facies F—Gray green to white and pink, massive, interbedded resistant and recessive thin beds, commonly friable, with few silty interbeds, 4–12 cm thick, bioturbated, mottled, lime mudstone with rare mollusk, bivalve, and barnacle shells preserved.

Facies G—Pink, tan, white, v.f.g. to f.g. sand, with small scale, unidirectional, asymmetrical ripples in fine grainstone containing abundant small scale reactivation surfaces with lime mudstone drapes. Interbedded with 3–4 cm of continuous parallel laminated fine grainstone beds with fossil hash and laminated very thin beds of white carbonate clay and silty clay. Ripple crests are rarely preserved.

Process Interpretation: Interbedded facies record deposition in tidal flat, back barrier tidal flats, and sheltered subtidal lagoons. Bundles of alternating thin and thick laminae are possibly tidal rhythmites (Figure 1, b), though detailed statistical analysis is needed to test an astronomical tidal process of deposition. Massive, mottled, and bioturbated beds are common of subtidal lagoonal environments (Laporte, 1971). *Thalassinoides* burrows are commonly formed by burrowing crustaceans in intertidal to shallow subtidal marine environments (Myrow, 1995).

(4) High-Energy Tidal Bar Association

Facies H –Tan brown weathered and white to gray fresh, massive crossbedded, alternating thin and thick crossbed sets of tan–white bioclastic grainstone hash with <5% siliclastic sediment, and tan–gray fine grainstone with ~30% siliciclastic sediment. Steep forests dip ~30° at top of massive (~3 m tall) crossbed sets (Figure 1, d). Bedding dips shallow laterally into flat-lying equivalent bottomsets, which grade laterally into small scale asymmetrical ripples with lime mud drapes (Figure 1, a), and those pass laterally into heterolithic sand-to mud rhythmites with flaser, wavy, and lenticular bedding of the Lagoonal and Tidal flat Marl association (Facies G and Facies E, respectively). Grainstone hash is more resistant to weathering, and gray fine grainstone is poorly indurated and recessive. Massive crossbed sets have abundant more gently dipping (~15–25°) erosive reactivation surfaces with common reverse ripples (Figure 1, c). Also common to this facies are ~10–15 cm thick, and up to 80 cm long tidal bundles with alternating thin and thick sigmoidal interbeds of grainstone hash and fine grainstone. Thin sigmoidal interbeds pass laterally into thick bottomsets, and thick sigmoidal interbeds may have thin or truncated, unpreserved bottomsets (Figure 2). Massive crossbed sets and sigmoidal tidal bundles have consistent paleocurrent directions toward the west on the east side of the basin, and to the east on the west side of the basin. Reverse ripples show transport directions opposite to the main crossbed and tidal bundle sets on both sides of the basin.

Shoaling-upward sequences—multiple shoaling-upward sequences are common in this facies association, and include vertical stacking of massive lime mudstone, heterolithic sand-to-mud rhythmites with flaser, wavy, and lenticular bedding, and ripples with reactivation surfaces (Facies F E and G, respectively, of the lagoonal and tidal flat marl association), that are overlain by massive crossbed sets with sigmoidal tidal bundles and reactivation surfaces (Facies H).

Process Interpretation: Sedimentary structures of this association display many criteria for recognition of tide-dominated deposits. They include: (1) lateral bundle/bottomset thickness variation; (2) possible bundle thickness variation that tracks cyclic astronomical cycles, though future statistical analysis will be needed to test a thickness variations ascribed to an astronomical tidal origin; (3) common reactivation surfaces with reverse ripples; and (4) common opposing bidirectional paleocurrents (Nio and Yang, 1991).

Massive crossbed sets of alternating thin and thick grainstone hash and fine grainstone are interpreted to record deposition by migrating tidal bars, with systematic hydraulic sorting of carbonate and siliciclastic sediment by tidal currents, under the influence of cyclic solar cycles. Grainstone hash likely records the subordinate current, and fine grainstone with a higher percentage of siliciclastic sediment likely records the dominant current (Longhitano, 2011). Reactivation surfaces are common in megaripple cross-bed sets, and are characteristic of alternating, but unequally strong tidal currents (Boersma, 1969; Klein, 1970), though these structures can also also occur in large lakes (Ainsworth et al., 2012). Reverse ripples on reactivation surfaces are characteristic tidal indicators, likely representing small opposing ripples that record the subordinate phase of deposition (Nio and Yang, 1991). Reverse ripples in these deposits are commonly bioclastic grainstone hash, further indicating that the subordinate phase is recorded by the bioclastic grainstone hash.

Lateral bottomset thickness variations are commonly observed. Thick bottomsets are related to thinner bundles, indicating that thick bottomsets are well-formed during neap tides. Conversely, thin or truncated bottomsets are equivalent to thick bundles that we interpret formed during spring tides (Figure 2). The process interpretation of thickening and thinning of bottomsets is as follows: during spring tides, the strong dominant current will have erosional power in the trough, producing a deep trough in front of the migrating ripple that results in poorly developed bottomsets. Conversely, during neap tides, weaker currents decrease the erosional power of the bottom vortex, favoring the formation of well-developed bottomsets (Nio and Yang, 1991).

Grainstone bars that pass laterally into heterolithic bedding likely represent deposition in low to middle intertidal setting, and from declining current energy and decrease in the sand to mud ratio laterally (Demicco and Hardie, 1994). These structures are commonly observed

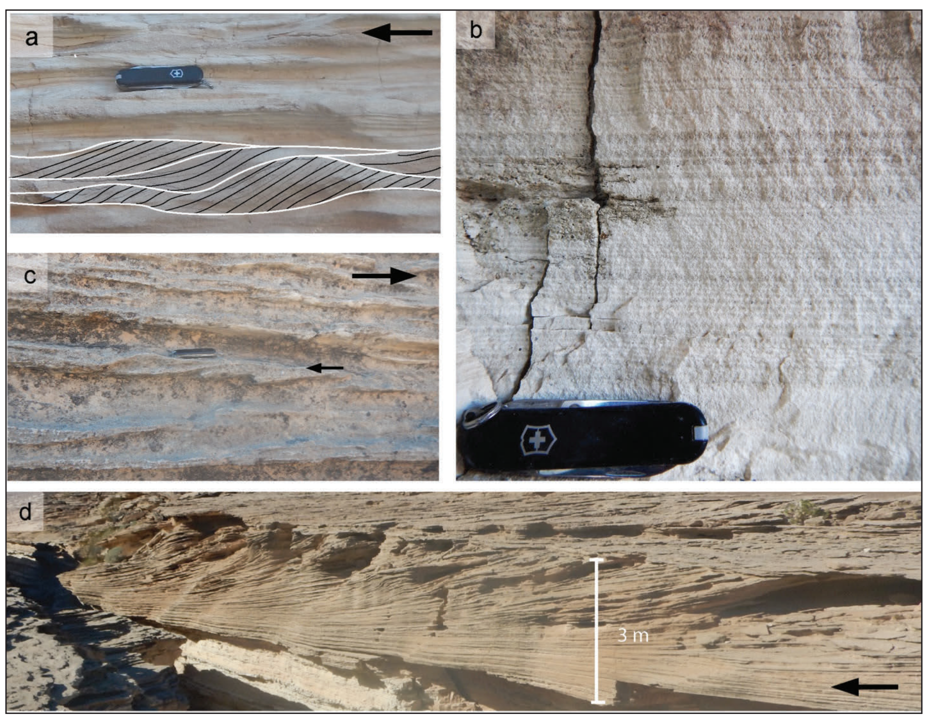

Figure 1. Arrows indicate flow direction. a) Marl drapes over unidirectional ripples (Low Energy, Lagoonal and Tidal Flat Association, Facies G): b) Possible tidal rhythmites of alternating thin and thick lamina (Low Energy, Lagoonal and Tidal Flat Association, Facies E). c) Reverse ripples on mega-crossbed set (High-Energy Tidal Bar Association, Facies H): and d) 3 meter-tall, mega-crossbed set with alternating beds of bioclastic grainstone hash and fine grainstone (High-Energy Tidal Bar Association, Facies H).

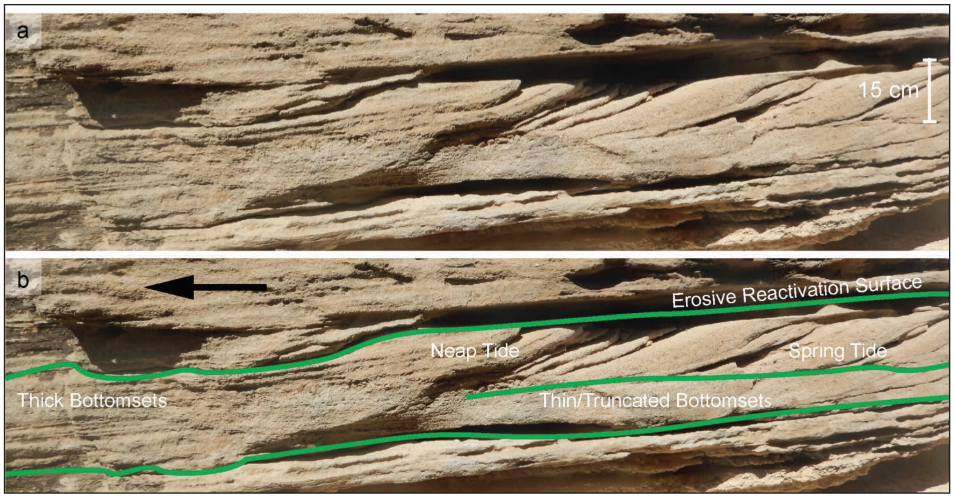

Figure 2. Possible tidal bundles in the High-Energy Tidal Bar association. Thick sigmoidal beds are interpreted the be deposited during spring tides, and thin sigmoidal interbeds are interpreted to be deposited during neap tides. Thick sigmoidal beds correspond to thin or truncated bottomsets, while thin sigmoidal beds correspond to thick bottomsets. Green lines indicate erosive reactivation surfaces interpreted to record erosion by the subordinate tidal current. Arrow indicates flow direction (East–West).

in ancient carbonate tidal deposits (Ghomashi, 2008; Lasemi, 1986; Lasemi et al., 2008). Systematic opposing bidirectional paleocurrent data of sigmoidal tidal bundles and mega-crossbed sets bundles are interpreted to record migration of tidal bars and bundles of 2D bedforms by tidal currents. The long axis of tidal bars forms parallel to tidal currents, and perpendicular to strike basin margin.

(4) Platform Margin Association

Facies I—Bioclastic barnacle and oncoid sandy grainstone to grainstone hash: Tan to white, coarse to very coarse, rounded to well-rounded, well-sorted barnacle and oncoid shell fragments. Sedimentary structures are well-exposed and include; (1) ripple cross lamination, (2) trough cross-bedding, (3) parallel lamination, (4) marl intraclasts, (7) lateral offshooting and bedform discordancy; and (8) bundled-upbuilding ripple lamination geometries. This facies is typically composed of >90% biological carbonate material, and the siliciclastic component is generally <20%. Grainstone facies pass laterally into packstone to wakestone interbedded with the lagoonal and tidal flat marl association and offshore micrite facies association. Paleocurrents of troughs are consistently oriented at 180°**.** This association is similar to the grainstone facies of the Tidal Bar Association (Facies H), however, can be distinguished by a lack of multiple shoaling upwards sequences, and a lack of mega-crossbed sets and sigmoidal bundles that shallow into flat-lying bottomsets.

Facies J—Wakestone and packstone barnacle oncoid hash. 5–12 cm thick beds of white, pale green, poorly sorted, unstratified to weakly stratified, lateral equivalents of bioclastic barnacle and oncoid sandy grainstone to grainstone hash. Commonly is interbedded with the lagoonal and tidal flat marl association and offshore lime mudstone facies association.

Process Interpretation: The high energy conditions of the platform margin results in development of coarse-grained carbonate sandy shoals that separate and protect the back-barrier tidal flat environment from the open basin (Purser and Evans, 1973). Wakestone to packstone represent lower energy equivalents of the grainstone facies, and are commonly interbedded and laterally interfingering with marl and micrite facies. Paleocurrents of trough crossbed sets are interpreted to record migration of 3D bedforms by unidirectional longshore currents.

(5) Subtidal Offshore Facies Association:

Facies K—Micrite (marl): white carbonate clay with interbedded carbonate paper shale thin beds (3–10cm) of very thinly laminated (1–3mm) clay, to thick massive beds of white marl with no internal structure and laminations. This unit is easily eroded and recessive, and systematically rests stratigraphically above the platform margin association.

Process Interpretation: subtidal offshore micrite—deposition by suspension settling and slow fallout of carbonate from ambient water column.

Stratigraphic architecture

The nearshore, lagoonal and tidal flat, tidal bar, platform margin, and offshore facies associations laterally interfinger and are locally interbedded with each other, indicating the time-transgressive nature of facies transitions. The overall stratigraphic architecture is a stacked transgressive assemblage, with the basal cobble lag overlain in order by nearshore, lagoonal and tidal flat with interbedded tidal bars, platform margin, to offshore facies associations. This vertical stacking of lateral interfingering facies associations clearly records an overall transgression in the basal carbonate member of the Bouse Formation prior to deposition of siliciclastic Colorado River delta and river-channel sequence.

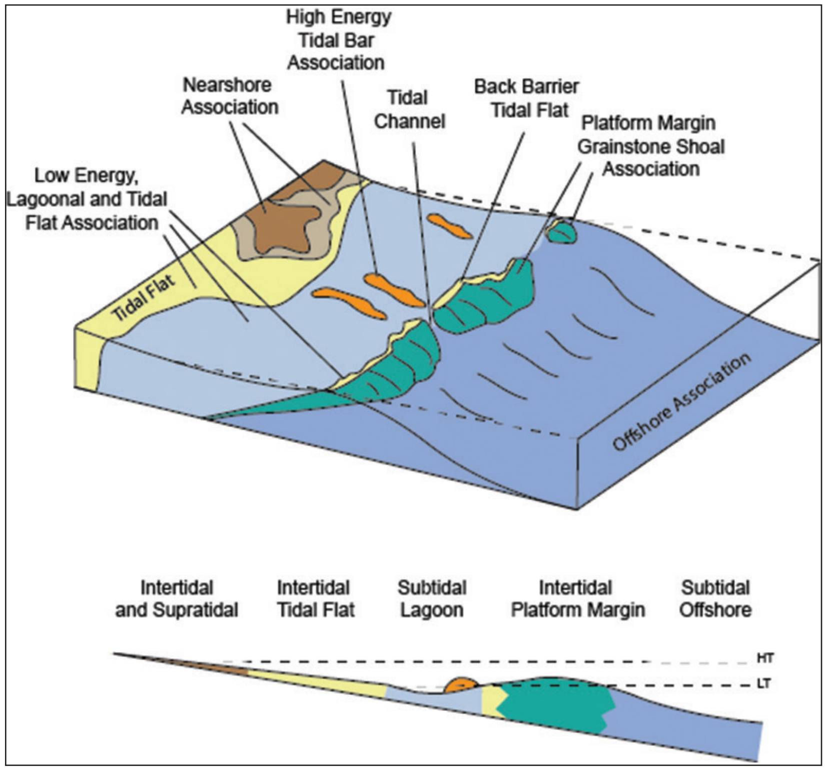

Figure 3. Mixed carbonate and siliciclastic platform depositional environments of the Bouse Formation. Abbreviations: HT high tide, LT low tide. Modified from (Lasemi et al., 2012), in *Principles of Tidal Sedimentology*.

Paleoenvironmetal interpretation and depositional model

A transgressive setting is recorded in the basal carbonate member of the Bouse Formation. Deposition occurred on a shallow mixed carbonate and siliciclastic platform with evidence for a strong tidal influence. As such, the Bouse basal carbonate likely records deposition in a basin with a marine influence. Important to this interpretation is the recognition of a low-energy shallow lagoonal and tidal flat association, and a high-energy tidal bar association that displays pervasive tidal structures. These include asymmetric ripples with reactivation surfaces and marl drapes, mega-ripples with reactivation surfaces, lateral bundle/bottomset thickness variation, rhythmic alterations of v.f.g sandstone and lime mudstone beds with flaser, wavy, and lenticular bedding that pass laterally into the high-energy tidal bar association, and systematic stacking of alternating thin and thick lamina of silt and lime mud. These structures are collectively interpreted to record deposition on a mixed tidal flat, and by migrating tidal bars. Many of these structures, particularly lateral bundle/bottomset thickness variation, and possible presence of bundle/rhythmite thickness variation that tracks astronomical solar cycles, match diagnostic sedimentologic criteria produced by tidal processes. While bundle thickness variations can also form in large lakes, they do not display cyclic thickness variations that record fluctuating current velocities and directions caused by daily, bimonthly, and monthly astronomical cycles. Instead they display an irregular organization that likely reflects flow-velocity and flow direction alterations (Ainsworth et al., 2012; Visser, 1980). As a test, future statistical analysis will be needed to test thickness variations ascribed to an astronomical tidal origin (e.g. Mazumder and Arima, 2005). Other criteria, such as mud drapes, reactivation surfaces, and wavy flaser and lenticular bedding, are excellent diagnostic tidal signatures, though they can form under non-tidal conditions (Ainsworth et al., 2012; Davis Jr, 2012). However, the abundance of characteristic tidal features, and their systematic vertical stacking in the southern Bouse Formation strongly suggest deposition in a tidally influenced transgressive depositional system (Davis Jr, 2012).

Conclusions

Five facies associations in the basal carbonate member of the Bouse Formation near Cibola, Arizona, are stacked in an overall transgressive vertical succession that accumulated before arrival of the siliciclastic Colorado River delta sequence. (1) The basal cobble lag is interpreted as forming by low to moderate energy currents along a transgressive ravinement surface. (2) The nearshore association is represented by golden gravel, sandy calcarenite and calcareous sandstone, and is interpreted as high-energy nearshore gravel bedforms and sandy bottomsets. (3) The low-energy lagoonal and tidal flat association is represented by mudcracked, heterolithic, silty to chalky silty marl with abundant wavy, flaser, and lenticular bedding with common reactivation surfaces. This association is interpreted to have accumulated in low- to moderate-energy subtidal lagoon and intertidal tidal flat environments. (4) The high-energy tidal bar association likely records hydraulic sorting of carbonate and siliciclastic material during migration of large tidal bedforms under the influence of persistent strong alternating tidal rip currents (5) The platform-margin association is represented by bioclastic barnacle and oncoid grainstone, wakestone and packstone, and interpreted as forming in high-energy platform-margin sandy shoals that protected the back-barrier lagoon and tidal flat association. The subtidal offshore association is represented by white, recessive micrite (marl) and carbonate paper shale that was deposited in quiet water by suspension settling of carbonate through an ambient water column.

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