

Upper limestone of the southern Bouse Formation: evidence for unsteady origins of the Colorado River

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Introduction

The latest Miocene to early Pliocene Bouse Formation contains an enigmatic record of conditions and processes that influenced the early evolution of the Colorado River. Our understanding of how the Colorado River became integrated and linked to the Gulf of California depends on interpretation of the Bouse Formation, but presently there is vigorous debate concerning Bouse depositional processes, environments, and chronology.

Below we describe the stratigraphy and sedimentology of the Bouse Formation south of Blythe, CA, with emphasis on an upper limestone unit that was not identified in previous studies. We briefly summarize the

occurrence, lithofacies, and depositional processes of the upper limestone, side-stepping for now the question of whether the Bouse formed in a marine estuary or a saline lake isolated from the ocean. We present evidence that the upper limestone formed in a large shallow standing body of water that hosted a variety of depositional environments, and it overlies cross-bedded Colorado River sandstone that appears to have formed in an early through-flowing river channel. Thus we propose that the upper limestone records inundation of the lower river valley by a regional lake or marine estuary *after* the river first ran through it.

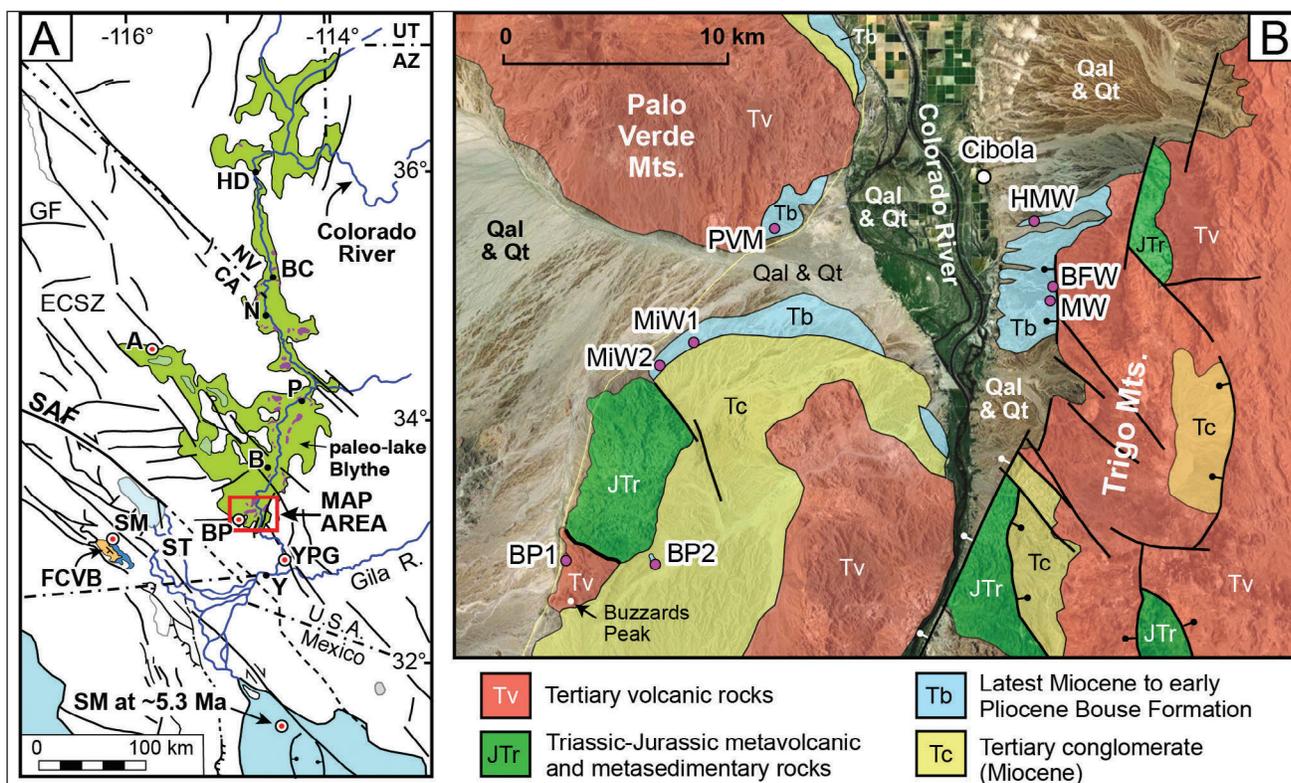


Figure 1A. Map of the lower Colorado River showing major faults, exposures of the Bouse Formation (purple), and Bouse paleo-Lake Blythe of Spencer et al. (2008). Abbreviations: A, Amboy; B, Blythe; BP, Buzzards Peak; C, Cibola; ECSZ, eastern CA shear zone; GF, Garlock fault; HD, Hoover Dam; N, Needles; P, Parker; SAF, San Andreas fault; SM, Split Mtn Gorge; ST, Salton Trough; Y, Yuma; YPG, Yuma Proving Ground. 1B. Simplified geologic map of the study area (compiled from Sherrod and Tosdal, 1991; Richard, 1993; Ricketts et al., 2011). Abbreviations: BFW, Big Fault Wash; HMW, Hart Mine Wash; MW, Marl Wash; MiW1 and MiW2, Milpitas Wash sections.

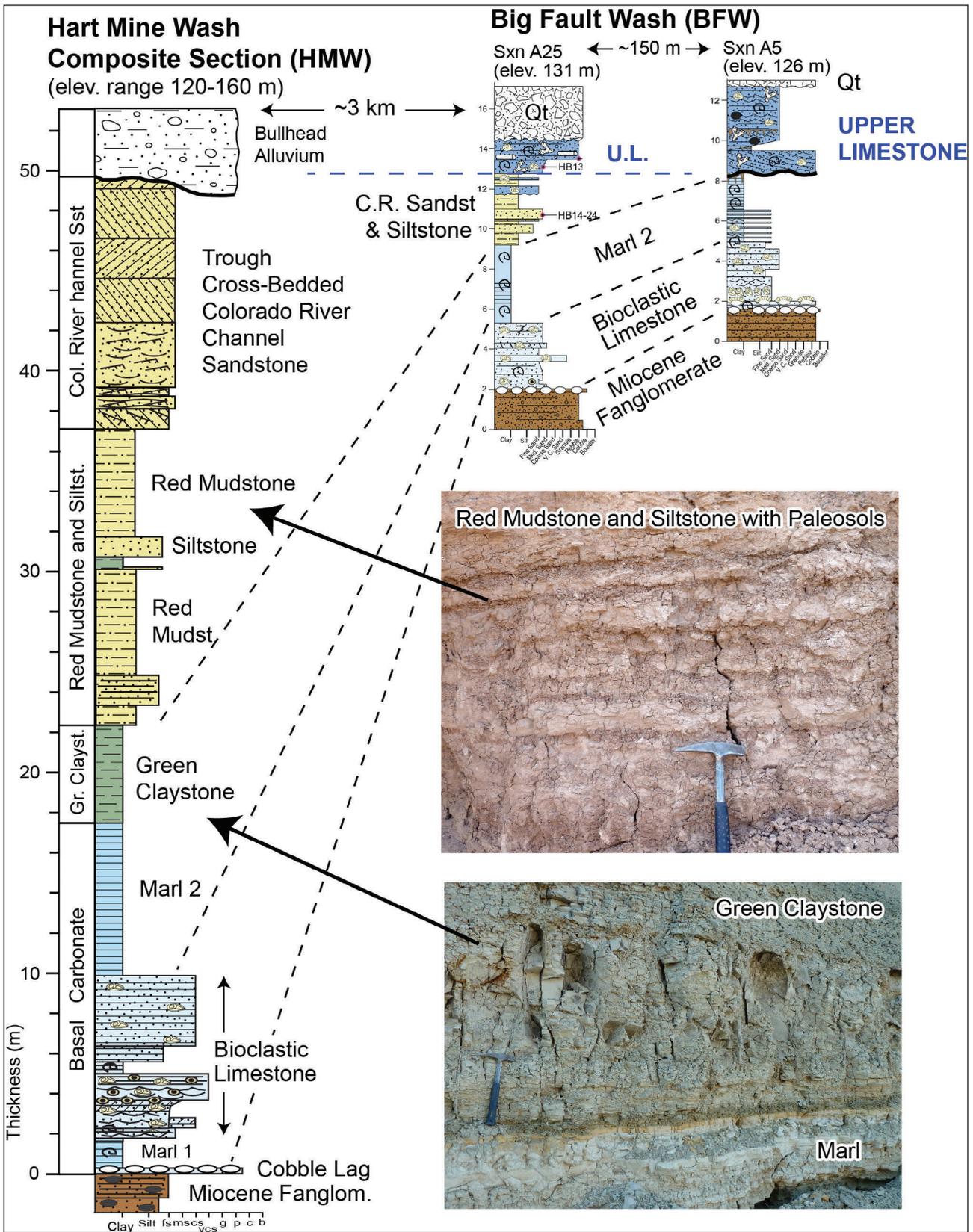


Figure 2. Correlated stratigraphic sections of the Bouse Formation southeast of Cibola, Arizona, showing basinward thickening and presence of Bouse upper limestone resting unconformably on Colorado River sandstone near the basin margin. Compiled and modified from Homan (2014). Locations in Figure 1. Photos of green claystone and red mudstone are from other localities of the southern Bouse Formation.

The new data and interpretations presented below are currently debated. We believe the data provide evidence for an unsteady, discontinuous style of river initiation that is not predicted by existing conceptual models. Plausible controls for this unexpected behavior may include changes in eustatic sea level, rate of basin subsidence, or rate of sediment supply to the basin. Discovery of the Bouse upper limestone reveals major gaps in our understanding of the early Colorado River, highlighting the need for new work to test our hypothesis for punctuated sediment flux and repeated flooding of the southern Bouse basin during the birth of this iconic river system.

Overview of the southern Bouse Formation

The Bouse Formation is a sequence of carbonate and siliciclastic deposits (Fig. 1; Metzger, 1968; Busing, 1990) that display stratal wedging, basinward thickening, and systematic pinch-out of units toward basin margins in the Cibola area (Homan, 2014). Bouse

basal carbonate deposits fine up from coarse-grained bioclastic limestone to fine-grained marl, and the marl is overlain by green claystone that pinches out on both sides of the Colorado River (Fig. 2). Green claystone is overlain by red mudstone and siltstone with locally developed desiccation cracks and paleosols – the presence of interbedded fine-grained Colorado River sand indicates that these deposits formed in the prograding Colorado River delta plain. In thicker expanded sections closer to the basin axis, red mudstone is overlain by thick, multi-storey, trough cross-bedded sandstone with minor mudstone in vertical exposures up to 17 m thick (Figs. 2, 3). Sandstone cross-bed sets are 1 to 3 m thick and fill erosional channels. Sedimentary structures include trough cross-bedding, climbing-ripple cross lamination, upper plane-bed stratification, and local convolute bedding. Sand is mostly fine-grained, and contains abundant well rounded hematite-stained quartz grains indicative of a Colorado River source (e.g., Winker, 1987; Busing, 1990).

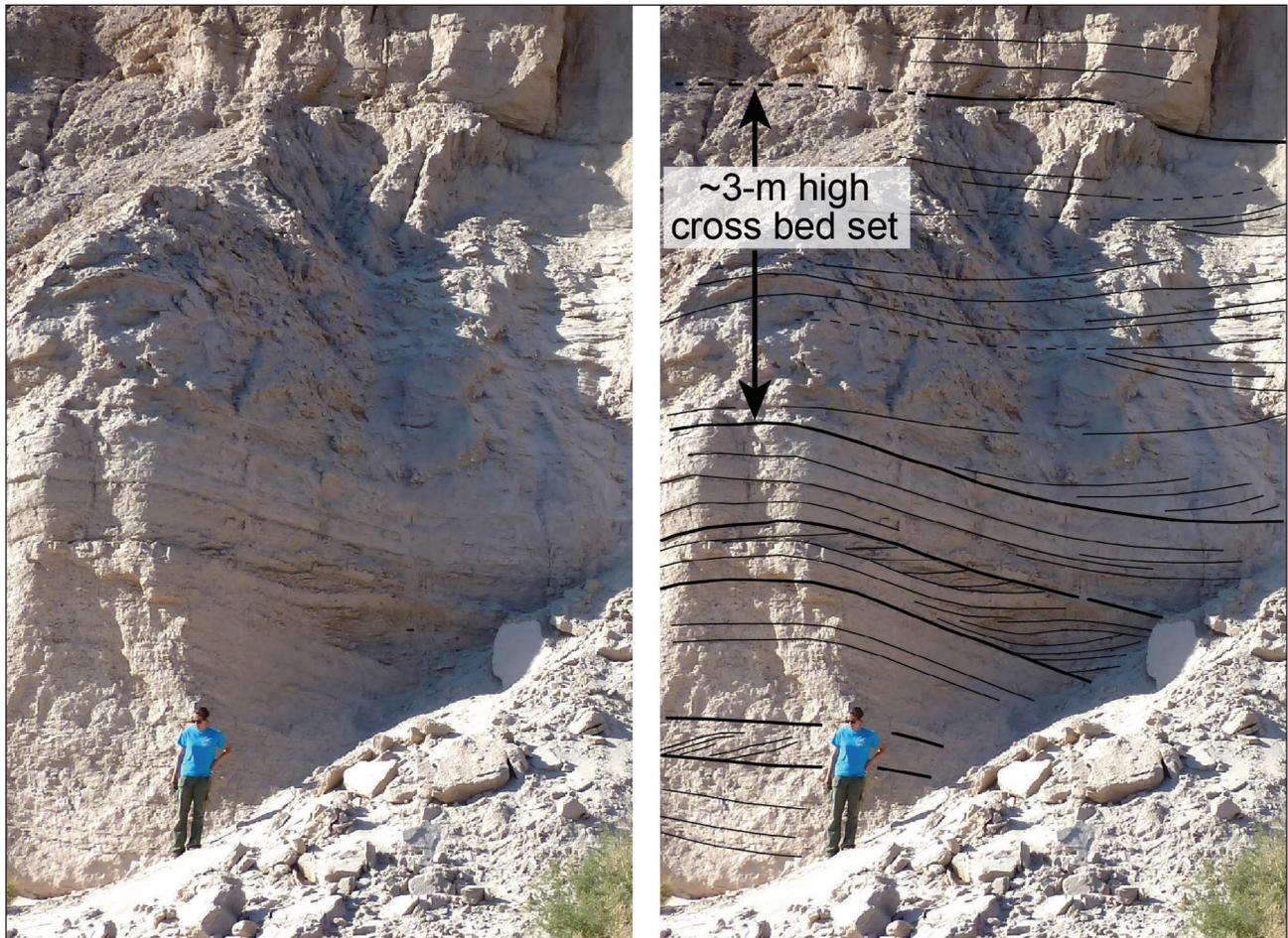


Figure 3. A. Outcrop photograph of thick, multi-storey trough cross-bedded channel sandstone of the southern Bouse Formation exposed in western Hart Mine Wash near the top of the Hart Mine Wash composite section (Fig. 2). B. Lines showing interpretation of channel-fill cross-bedding in A

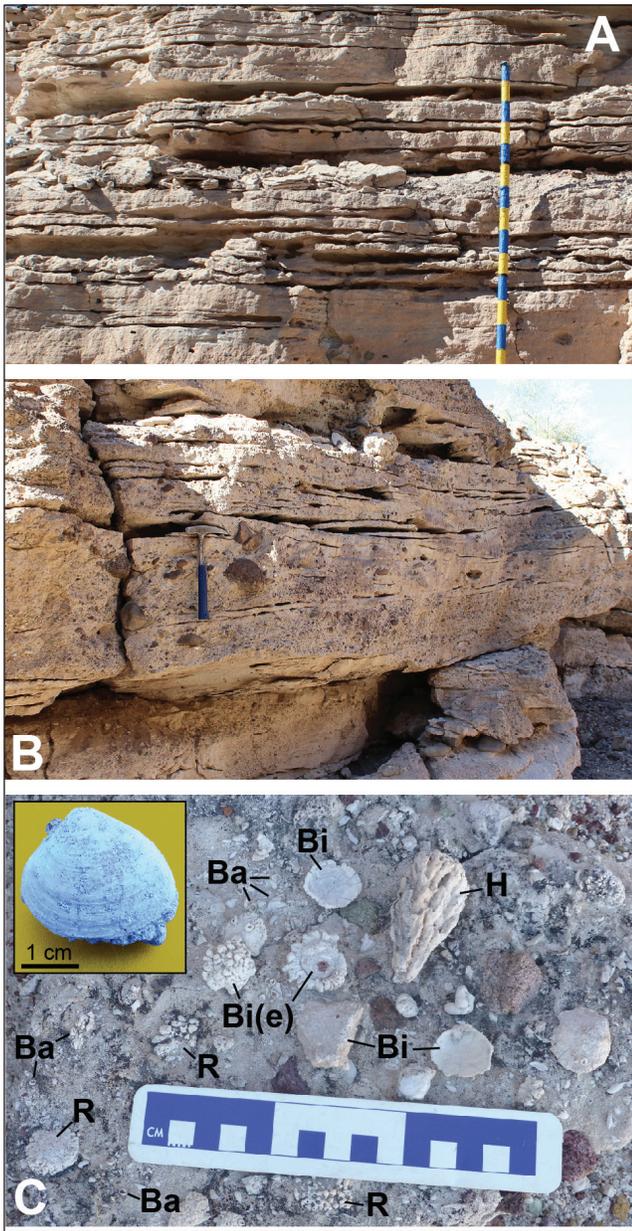
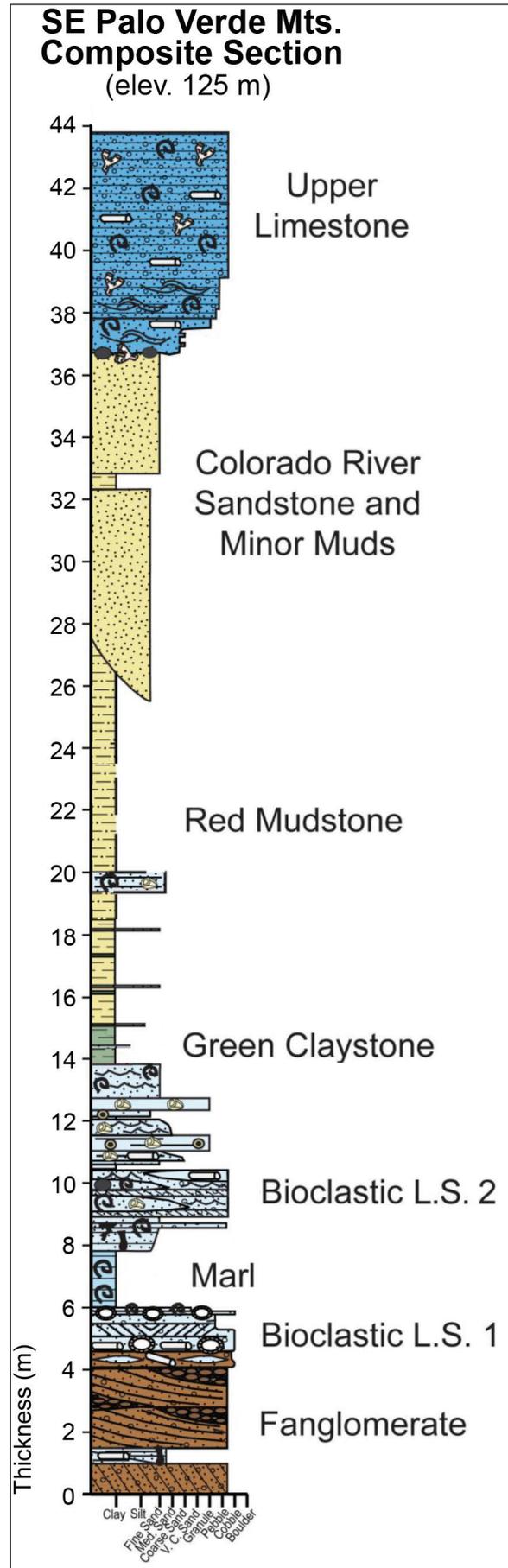


Figure 4 (above). (A) Sandy calcarenite of the upper limestone with abundant wave-ripple lamination. (B) Long-wavelength, convex-up hummocky cross stratification in the upper limestone. (C) Bedding-plane slab of upper limestone with selected fossils: Ba, barnacles; Bi, broken abraded bivalve shells; Bi(e), bivalve shells encrusted with barnacles and calcareous algae; H, branching green algae *Halimeda*; R, rhodoliths (coralline red algae). Inset shows detail of an intact, unabraded small bivalve (likely *Polymesoda*).

Figure 5 (right). Composite stratigraphic section of Bouse Formation in the southeast Palo Verde Mts. Compiled from Homan (2014). See location in Figure 1.



We interpret the Bouse basal carbonate to record a transition from high-energy shallow water environments (bioclastic limestone) to deposition of marl by suspension settling below wave base in a large lake or marine estuary. Green claystone records an abrupt end of carbonate deposition. Association with overlying interbedded Colorado River sandstone suggests that the green claystone records first arrival of the most distal fraction of Colorado River-derived sediment. Red mudstone and siltstone accumulated in shallow-water mudflats of the encroaching Colorado River delta plain. Distinctive sedimentary structures and facies architecture of multi-storey cross-bedded sandstone indicate that it accumulated in an upper-delta-plain or fully fluvial channel of the early Colorado River (e.g., Bridge and Diemer, 1983; Reading, 1986; Miall, 1996; Martinsen et al., 1999; Holbrook, 2001). Because river-channel sandstone is not incised into units older than red mudstone, we conclude that it accumulated during a base-level highstand in response to increased sediment supply, not base-level lowering. This is defined as “normal regression” in sequence stratigraphic terminology (e.g., Catuneanu et al., 2009).

Bouse upper limestone

The upper limestone of the Bouse Formation is exposed on both sides of the river in the Cibola–Milpitas area where it overlies Bouse Colorado River sandstone and older units (Fig. 1). It typically coarsens up-section from (1) fine-grained wave-ripple laminated sandy calcarenite with interbedded Colorado River mudstone or siltstone near the base (Fig. 4A); to (2) poorly sorted pebbly calcarenite with flat-based, convex-up bedforms that resemble gravelly hummocky cross stratification (Fig. 4B); to (3) horizontally stratified calcarenitic-matrix conglomerate with clasts derived from nearby local catchments. Fossils include distinctive branching calcareous green algae (*Halimeda*) typically preserved as subrounded pebble-to cobble-size clasts, coralline red algae, rhodoliths, barnacles, and bivalves (*Polymesoda* and *Macoma*; A. Hendy, written comm., 2015) that are heavily encrusted with barnacles and calcareous algae (Fig. 4C).

The presence of water-lain sedimentary structures, articulated fragile bivalves, and high carbonate content all indicate that the upper limestone accumulated in a shallow, carbonate-producing, high-energy standing body of water. Some carbonate may be derived from reworking of older Bouse bioclastic deposits, but

reworking alone cannot explain the high concentration of carbonate and preservation of delicate mollusk fossils. Based on the distinctive water-lain sedimentary structures and evidence summarized above, we conclude that the Bouse upper limestone accumulated in a large shallow standing body of water. Coarsening up from wave-rippled sandy calcarenite to stratified poorly-sorted gravel records progradation of locally sourced shelf-type (shoal-water) fan deltas, which are well documented in other shallow-water basins (e.g., Ethridge and Wescott, 1984; Nemeč, 1990). A lateral facies change to thin-bedded micrite with desiccation cracks in the western Milpitas area records deposition in large low-energy carbonate mudflats and may support correlation to the Buzzards Peak area (Fig. 1).

The Bouse upper limestone overlies Colorado River sandstone and mudstone in thicker expanded sections of the Bouse Formation that are located closer to the basin center (e.g., Fig. 5), and it rests directly on Bouse basal carbonate close to the margins of the basin where siliciclastic sandstone and claystone are absent due to stratal pinch-out (Figs. 2, 6, 7; see Homan, 2014, for detailed data and interpretations). Basinward thickening and wedging in the Cibola area provide evidence for gentle tilting toward the basin center – now located beneath the modern Colorado River channel – during deposition of Bouse basal carbonate and siliciclastic units (Homan, 2014). The upper limestone also thickens locally toward a basin-bounding normal fault south of Cibola, preserving a record of syn-depositional monocline growth due to upward propagation and breaching of the fault tip at the Earth's surface (O'Connell et al., 2015).

In the western Milpitas Wash area, Bouse upper limestone rests unconformably on fine-grained marl of the Bouse basal carbonate that thins to the west from ~5.5 m in section C13 to ~30 cm in section C27 (Figs. 1, 6), likely due to erosional truncation of the basal marl. The upper limestone is easily recognized in these sections on the basis of its unique stratigraphic position and coarse dirty calcarenite with common *Halimeda* fragments. In this area the upper limestone includes fine-grained calcarenite and thin-bedded micrite with desiccation cracks, representing a muddy low-energy variant that is not observed in coarse-grained facies elsewhere. The upper limestone at section C27 overlies a discontinuous 10- to 15-cm thick gray ash bed that may correlate to the Lawlor Tuff near Buzzards peak (Fig. 1).

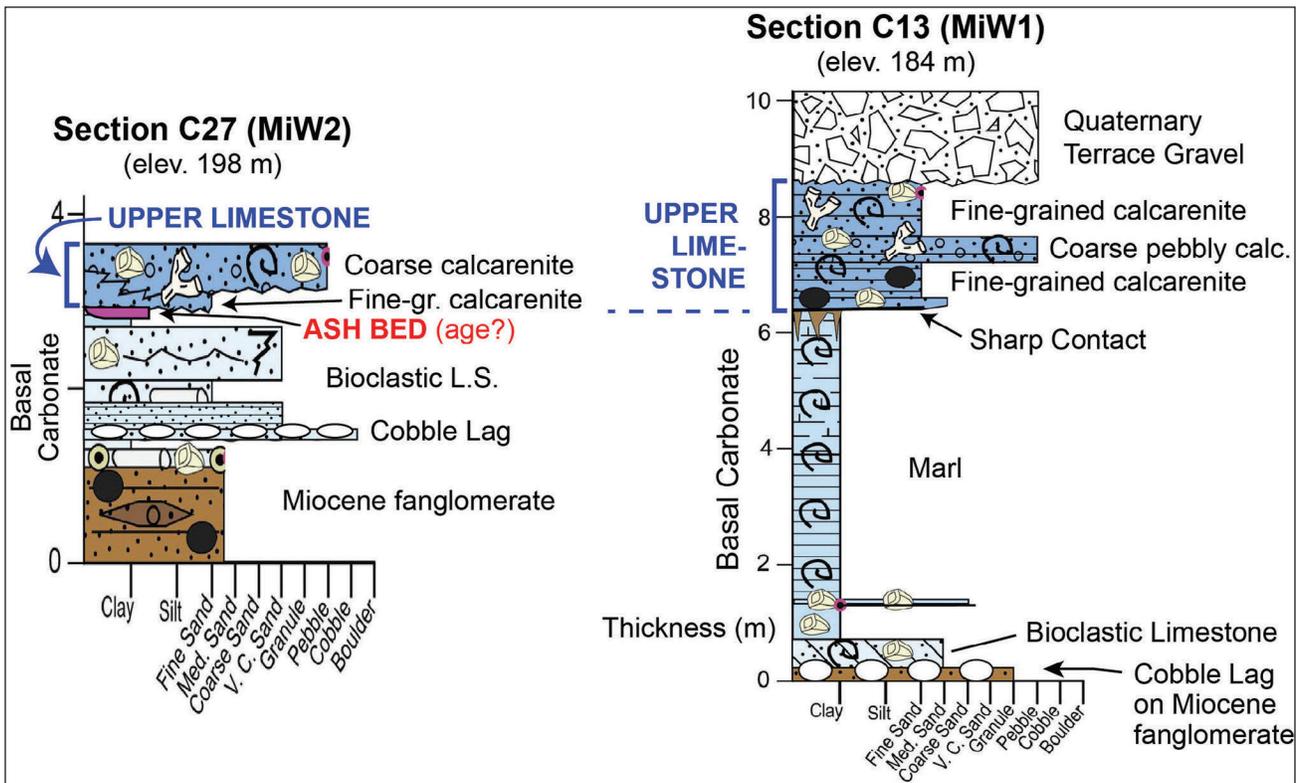


Figure 6. Two measured sections in western Milpitas Wash area where the Bouse Formation is capped by the upper limestone unit (modified from Homan, 2014). See Figure 1 for location.

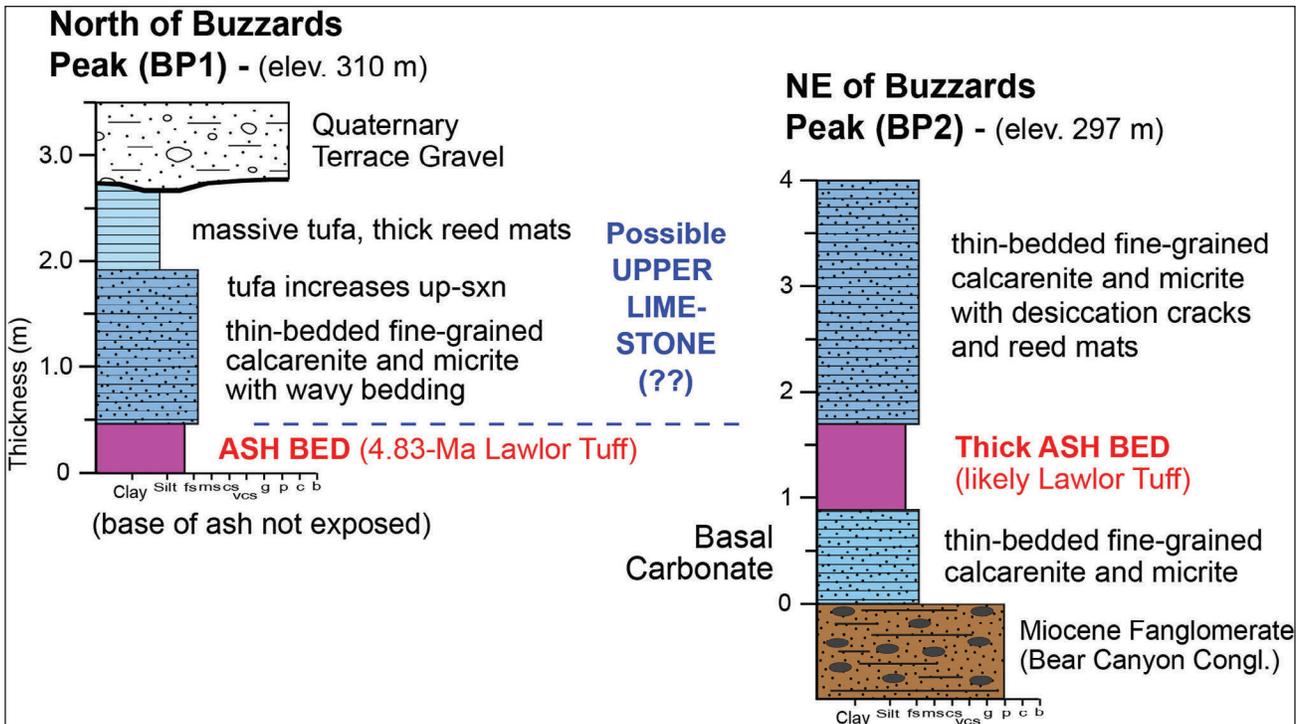


Figure 7. Two stratigraphic sections near Buzzards Peak. The 4.83-Ma Lawlor tuff is identified at section BP1 (Sarna-Wojcicki et al., 2011) and likely correlates to the thick gray ash interbedded with Bouse calcarenite and micrite in section BP2. Carbonate facies at section BP2 resemble facies at C27.

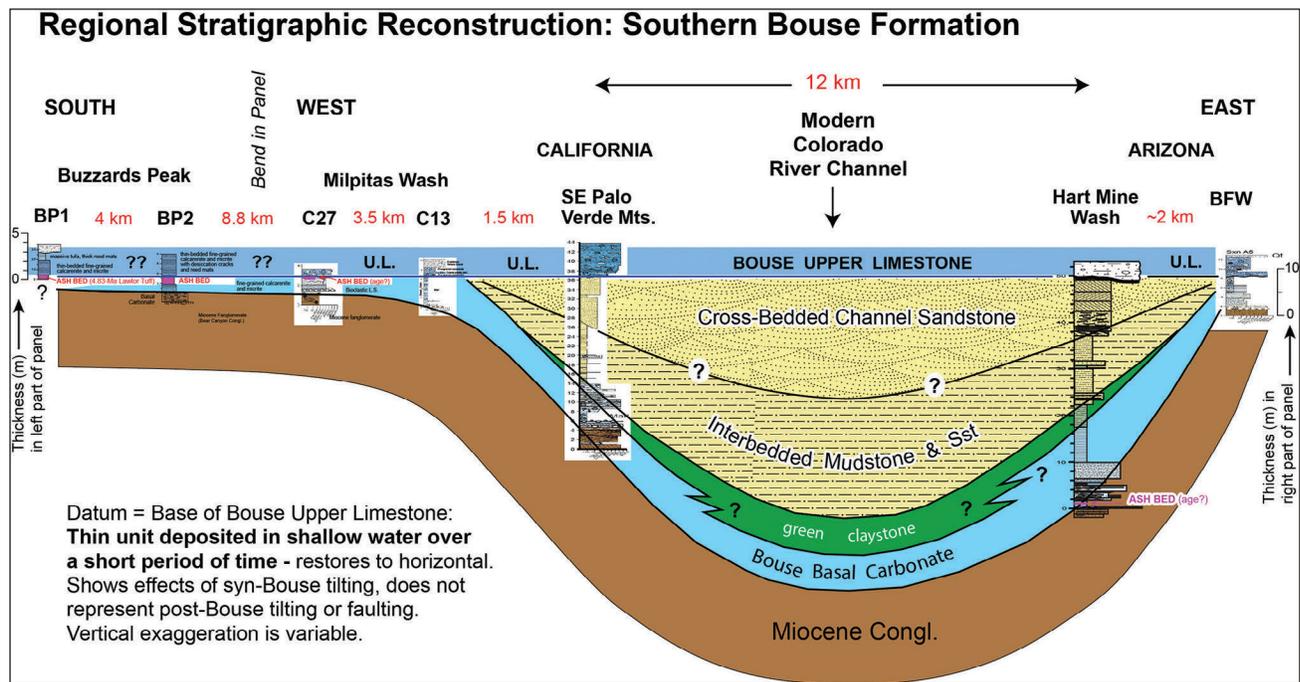


Figure 8. Proposed stratigraphic reconstruction of the southern Bouse Formation. See text for discussion.

Efforts are currently under way to analyze and date this recently discovered volcanic ash deposit.

At section BP1 near Buzzards Peak (Fig. 7), carbonate of the Bouse Formation overlies the 4.83-Ma Lawlor Tuff which has been identified using tephrochronology (Sarna-Wojcicki et al., 2011) and U–Pb dating of zircon (Harvey, 2014). Here the carbonate consists of fine-grained thin-bedded calcarenite and micrite that grade up-section into massive tufa with thick calcified reed mats. At section BP2 to the east, a similar undated meter-thick gray ash bed that likely correlates to the Lawlor Tuff is interbedded with flaggy thin-bedded calcarenite and micrite with desiccation cracks and reed mats, similar to carbonate facies seen in section BP1 (Fig. 7).

We suggest that post-Lawlor Tuff carbonate at sections BP1 and BP2 may be equivalent to the Bouse upper limestone, based on lateral facies changes in the upper limestone (i.e. westward change to fine-grained micrite) and presence of a thin gray ash directly beneath fine-grained calcarenite and micrite of the upper limestone in the western Milpitas Wash area. This idea is an alternative to existing models which assume that limestone at Buzzards Peak correlates to the Bouse basal carbonate (e.g., Spencer et al., 2013), and needs to be tested in future work.

The proposed stratigraphic reconstruction in Figure 8 highlights the newly recognized upper limestone of the southern Bouse Formation. Upper limestone overlies

thick cross-bedded sandstone that thickens toward the center of a large sag basin in the subsurface below the modern Colorado River channel. Around the margins of the sag basin, sandstone and mudstone units are missing and upper limestone rests directly on basal carbonate (Fig. 8). These relationships are clearly displayed in multiple locations around the Cibola–Milpitas–Palo Verde Mts region (Homan, 2014, this study), and are independent of whether or not the carbonate resting on Lawlor tuff at Buzzards Peak correlates to the Bouse upper limestone. Such a correlation would simplify the regional chronology but does not affect our interpretation of the upper limestone, which is based on fundamental concepts in process sedimentology and sequence stratigraphy.

Discussion

Thick multi-storey trough cross-bedded sandstone with stacked cross-bed sets up to 3–4 m thick in the Bouse Formation provide evidence for deposition by migrating dune bedforms in a large river channel complex, not small distributary channels in a distal delta plain or subaqueous delta front setting. We arrive at this conclusion through comparison of observed sedimentary structures and facies architecture to a rich literature of studies in fluvial process sedimentology (e.g., Bridge and Diemer, 1983; Reading, 1986; Miall, 1996; Martinsen et al.; 1999; Holbrook, 2001). Accordingly, we conclude

that the thick, nested cross-bedded sandstone facies overlying red mudstone with paleosols accumulated in either an upper-delta-plain or fully fluvial river channel complex. A through-flowing river interpretation is supported by recognition of cross-bedded Colorado River sands and muds beneath chert- and petrified-wood-bearing stratified gravel correlated to the Bullhead Alluvium at the Yuma Proving Ground Headquarters south of the Chocolate Mountains (Dorsey, unpubl. data), which implies that the Colorado River flowed through to Yuma prior to deposition of the Bullhead Alluvium. An early, pre-4.8 Ma through-flowing Colorado River would be consistent with first arrival of Colorado River sand in the Salton Trough at ~5.3 Ma (Dorsey et al., 2007, 2011; Kimbrough et al., 2015) followed by regional shut-down of sand delivery to the marine realm that produced the widespread marine Coyote Clay (Dorsey and Bykerk-Kauffman, 2015). The stratigraphic relationships documented in this paper do not depend on correlation to the Salton Trough. Nonetheless, data and observations from both regions suggest that the Colorado River turned ON, then OFF, then ON again during a short period of time. If these independent records do *not* correlate with each other, then the implied sequence of events would be more complex but not implausible.

There are four main reasons why we conclude that the Bouse upper limestone was deposited in a standing body of water (lake or marine estuary), and was not formed solely by reworking and redeposition of older carbonate material in alluvial fans around the margins of a draining, falling lake: (1) high carbonate content, which is >50% or >>50% in the micrite, sandy calcarenite, and calcarenitic-matrix conglomerate facies (Fig. 4A, 4B); (2) first appearance and common occurrence of the distinctive branching green algae *Halimeda* (Fig. 4C), which we have not found in older deposits of the Bouse basal carbonate; (3) abundance of distinctive water-lain sedimentary structures including symmetrical wave-ripple lamination and long-wave-length convex-up flat-based cross bedding that closely resembles hummocky cross-stratification (Fig. 4A, 4B) and is a common product of strong storm waves on high energy coarse-grained shelves (e.g. Clifton, 1986; DeCelles, 1987); and (4) in finer-grained facies, preservation of articulated, thin-shelled mollusks (Fig. 4C) that could not be expected to survive erosional reworking and abrasion in an alluvial fan environment. For these reasons, we conclude that the upper limestone records

re-flooding of the southern Colorado River valley by a large shallow standing body of water after the river first ran through it. This suggests to us a history of unsteady, punctuated sand transport through the southern river corridor during initiation of the Colorado River that is not predicted by existing conceptual models. The upper limestone, and a likely correlative thin claystone unit in the Salton Trough, appear to record shut-down of sand through-put by the river for ~200 kyr at about 5 Ma, followed by rapid progradation of sediment into the Gulf of California during deposition of the Bullhead Alluvium (Dorsey et al., 2011; Howard et al., 2015; Dorsey and Bykerk-Kauffman, 2015). The short-lived hiatus in sediment discharge by the early Colorado River is a significant finding of this study, and requires an explanation.

The implied discontinuous, start-and-stop history of sand flux during river initiation may have been controlled by variations in sediment discharge from the upper catchment (Colorado Plateau), or by changing production of accommodation space along the lower river corridor. Although it is difficult to test for changes in early Pliocene paleo-erosion rate, there are several mechanisms that could have produced changes in the rate of production of accommodation space and trapped sand for a short time along the river corridor south of Grand Canyon, including: (i) global eustatic sea-level rise, if the southern part of the Bouse Formation accumulated in a marine estuary; (ii) increased subsidence rate south of Lake Mead, including possibly in the deep Mohave Valley and Blythe Basin related to releasing step-over faults of the Eastern California Shear Zone; or (iii) construction of a tectonic dam by uplift along the San Andreas fault in the Chocolate Mountains, which could have re-flooded paleo-Lake Blythe and temporarily trapped sand in the Parker area. Future work is needed to further test and refine our hypothesis for discontinuous sediment flux, and assess the possible controls on this unexpected behavior during the birth and the early evolution of the Colorado River system.

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