Travertines of the Bouse Formation

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The Bouse Formation provides a sedimentary record of the first arrival of the Colorado River, water and sediment, as it was integrated from the Colorado Plateau to the Gulf of California 5–6 Ma. This unit is generally thin (10–100s m) but widespread within basins in the lower Colorado River corridor that extend from Lake Mead to Yuma (Fig. 1). The basins are interpreted to have been previously internally drained areas that were integrated basin-to-basin by the Colorado River (e.g., Spencer et al., 2008; 2013), although marine/estuarine inundation has been proposed for the southern part of the corridor (e.g., Miller et al., 2014; McDougall and Miranda-Martinez, 2014). The lower parts of the Bouse Formation are predominantly carbonates; the upper part (the interbedded unit) consists mainly of siliciclastic deposits, including Colorado River muds and sands.

This paper focuses on the carbonate facies of the Bouse with a goal of understanding the different types and origins of Bouse carbonates. Dorsey et al. (this volume) describe three carbonate facies in the southernmost part of the corridor: (1) lower bioclastic limestone and minor tufa that are interpreted to represent high-energy shallow water (including tidal) environments; (2) a marl succession that is interpreted to record precipitated carbonate settling below wave base in a large body of water; and (3) an upper unit of fossil-rich calcarenite and conglomerate (Gootee et al., this volume) that overlies the other carbonate facies, mudstone, and cross-bedded Colorado River sandstone. Dorsey et al (this volume) interpret this upper unit as evidence of reinundation of an early Colorado River valley by a lake or estuary; Gootee et al (this volume) suggest that the upper unit is a mix of local tributary siliciclastic material and carbonate reworked from the lower two carbonate units as the water level in the valley receded.

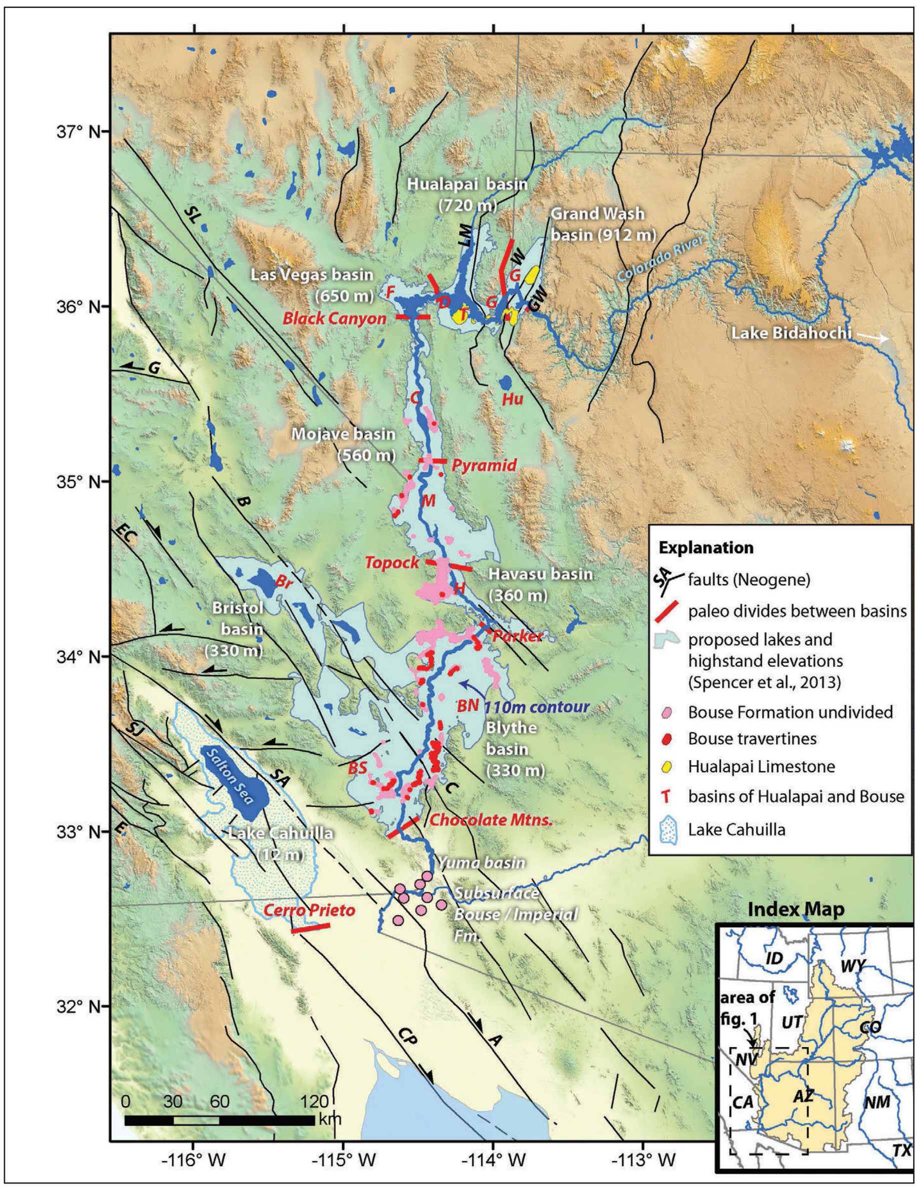

Figure 1. Distribution of the Bouse Formation; Red= Bouse travertine; Pink= Bouse Fm. undivided.

Figure 2. Textures of Bouse travertine: A. coarse travertine drape on basement schist; B. radial crystal fabric perpendicular to growth banding; C. botryoidal infillings in cave within mound deposit; D. fine grained calcite (spar) filling vein; E. weathering of large spherical botryoids; F. possible stromatolitic dome

Travertines (aka tufas) have now been mapped in numerous places by the U.S. Geological Survey and Arizona Geological Survey as part of the Bouse Formation (Fig. 1); they provide another carbonate facies that needs explanation. The term travertine is used here as the more inclusive term and refers to "chemically-precipitated continental limestone that forms as groundwater discharge deposits at spring outlets, and in lakes and streams, via precipitation of calcite from waters that are supersaturated with respect to calcium carbonate" (Ford and Pedley, 1996; Pentecost, 2005). The term "tufa" is sometimes used interchangeably as a mapping term for porous carbonates that occur in spring mounds and "tufa towers" around lakes. However, we prefer the term "travertine" and use it inclusively to include hot, warm, and ambient temperature groundwater discharge deposits, i.e. with no implied interpretation about temperature of the depositing waters, as this is generally unknown for inactive systems. The term travertine, in our usage, also encompasses the

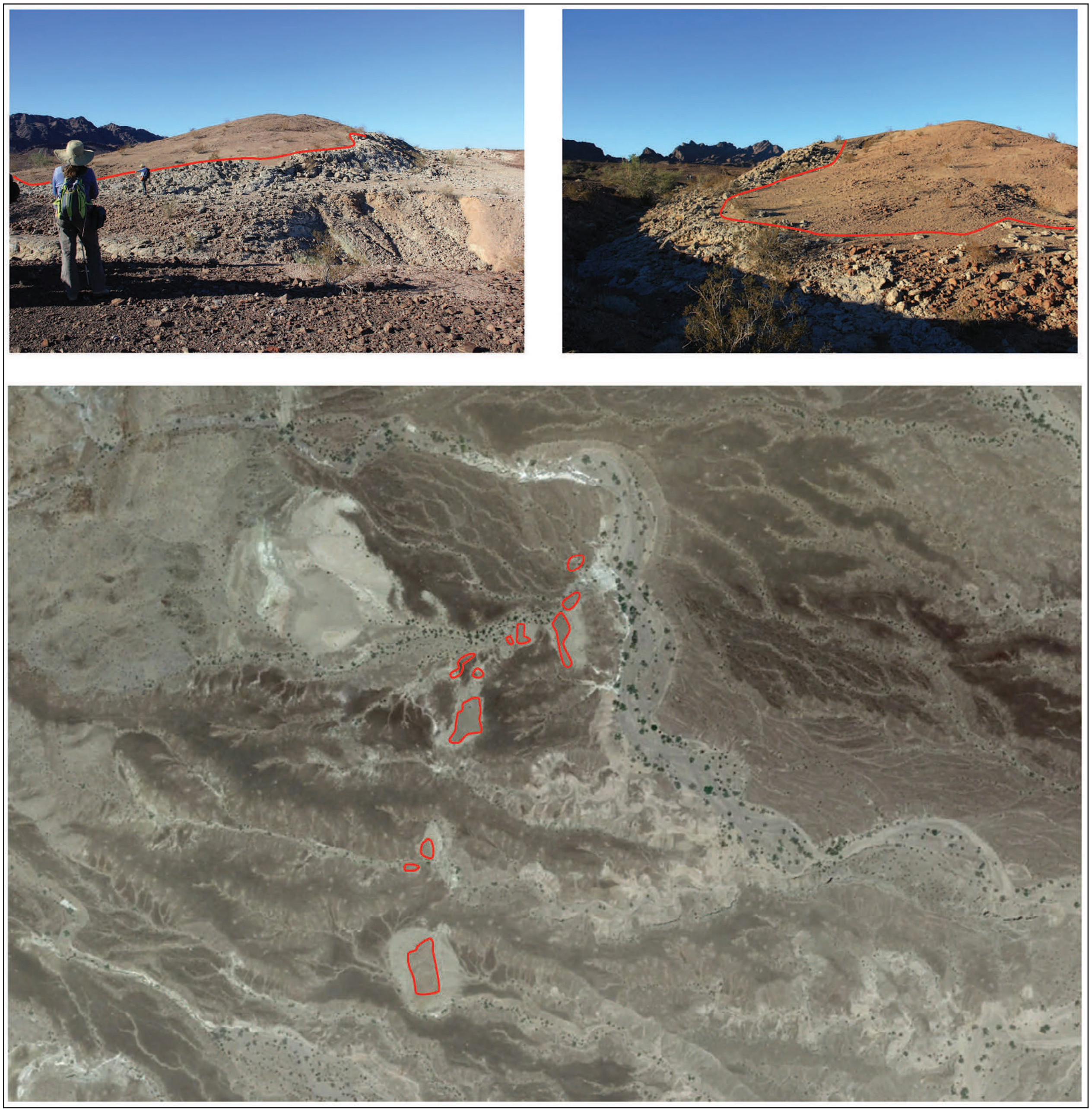

Figure 3. Travertine rimming paleotopography in Palo Verde Mountain area suggests deposits are related to basin shorelines. Google Earth image shows travertine rimming multiple hills at approximately the same elevation along linear trends.

full range of textures such as porous bedded travertine (Fig. 2A), carbonate with radial crystallographic fabric perpendicular to growth banding (Fig. 2B), botryoidal travertines filling open space in mound complexes (Fig. 2C), laminated fine grained calcite veins (Fig. 2D), stromatolites interpreted as algal mats cemented by calcite (Fig. 2F), travertine step-pool facies, marsh stick-cast facies, and others. Used in this way the term travertine can be further embellished with specific textural and interpretive descriptions (see below), and it serves to distinguish a set of carbonate facies that record something different than the bioclastic, marl, and calcarenite facies of the Bouse Formation.

Travertines (fresh-water carbonate deposits) form according to the following reactions (Pentecost, 2005; Crossey et al., 2006, 2009). For waters to become supersaturated with respect to CO2, an "external" CO2 source (e.g. soil gas and/or magmatically derived volatiles) is needed to make waters aggressive enough to dissolve calcite in regional aquifers. The dissolution reaction is: $extCO_2(g) + H_2O + CaCO_3(limestone) \rightarrow Ca_2+(aq) + 2HCO_3 -(aq)$. The precipitation phase of

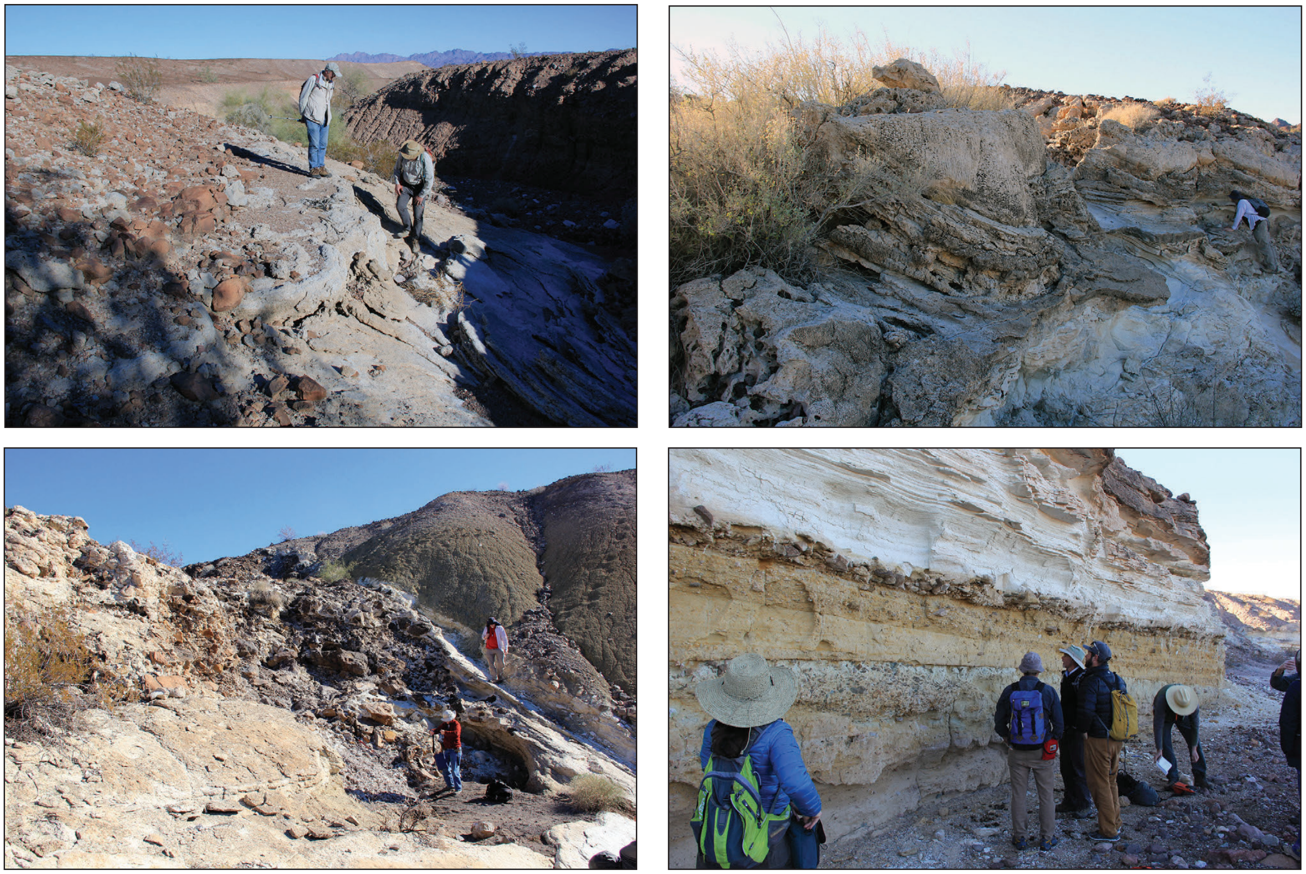

Figure 4. Evidence that travertine deposits pre-date Bouse marls at multiple localities: A. and B. Palo Verde Mountain area has marls inset as apparent shoreline deposits against travertine/ tufa mounds or towers; C. travertine-cemented talus overlain by marl; D. clasts of rounded coarse grained travertine/tufa underlie marls in Hart Mine Wash

travertine involves degassing of CO_2 due to pressure drop (as artesian waters move upward) and/or turbulence (e.g. due to small waterfalls and wave action) via the reaction: Ca_2+(aq) + 2HCO_3 -(aq) → CO_2(g)↑+ H_2O + $CaCO_3$(travertine). Biological influences can also facilitate travertine precipitation of calcite by changing saturation state of waters or by algal trapping of fine grained carbonate. Bouse travertines are interpreted here as primarily due to degassing, but perhaps locally amplified by biologic processes.

Bouse travertines are found in all sub-basins, but are most voluminous in the Blythe basin. They occur on both east and west sides of the basins, and may be particularly extensive at particular elevations ranges. They tend to occur in conjunction with nearshore gravel deposits and are found in numerous locations draped against bedrock of a variety of lithologies (Fig. 2A). In the Mohave and Blythe basins, they transect from lowest to highest elevations suggesting time transgressive deposition. Outcrop geometries range from drapes on underlying paleotopography, large mound complexes (Fig. 2E), and deposits that are concentric around paleotopography (Fig. 3). Relationships with other Bouse facies are observed in several places and indicate that travertine accumulations generally existed as topographic features against which horizontal marls and bioclastic and marl carbonates were inset (Fig. 4 A, B), including examples of travertine-cemented talus overlain by marl and green claystone (Fig. 4C). In other areas, small concentrations of travertine are found within bioclastic limestone and nearshore marl deposits. Travertine-coated cobbles and boulders, and clasts of travertine are also found in the lag gravels and fanglomerates below the basal Bouse bioclastic carbonate (Fig. 4D). Thus, we infer that Bouse travertines are likely time transgressive (timescale unknown) but were deposited mainly before other Bouse carbonates were deposited on top of them at a given locality. Closest analogs seem to be tufa mounds and shoreline tufas of Pyramid Lake and Lake Lahontan (Benson, 2004), tufa mounds in Mono Lake (Dunn, 1953; Scholl and Taft, 1964), stromatolites in groundwater springs (Wolaver et al., 2013), and shoreline deposits around both marine and lake basins. Using these analogs, we suspect that additional mapping may reveal a combination of geothermal inputs along faults and lake-margin deposition that reflects shoreline wave action.

Although additional mapping is needed to test depositional models, the distribution of travertine outcrops suggests two likely controls on deposition. Fault control seems likely to source excess CO_2 and locate springs along fault conduits. However, preserved travertine deposits are quite extensive in some areas, and no direct fault–travertine associations are yet documented. Lake shore origin for the travertine is thus our preferred interpretation for the occurrences seen to date as this might provide turbulence needed for degassing, form the concentric geometry of travertine outcrops around paleotopography, and explain the general association of travertine with basin highstands in terms of a basin transgression. If so, the presence of similar mound complexes at low elevations and drapes across paleotopography might be ascribed to basin transgression with travertine older than other carbonate facies at any location.

Geochemical tests for origin of the travertine are underway and include multi-tracer analysis of travertine versus other Bouse carbonate facies. If spring inputs were important sources, the travertine may show high $^{87}Sr/^{86}Sr$ especially when groundwater flowpaths were through Precambrian granites. The presence of silica and geothermal-associated trace elements like B, Br, Li may help establish any geothermal inputs. A lakeshore origin may show significant degassing and fractionation of stable isotopes. Another important aspect of travertine is that they may be datable using U–Pb dating to help establish the timeframe for Bouse deposition. For example, in the current spill-and-fill model for downward integration of the Colorado River system (Spencer et al., 2013; Pearthree and House, 2014), travertine deposits record rising lake levels. With progressive filling and spilling of basins, travertine deposits in higher basins travertines would generally be older than lower basins. Depending on how rapidly these postulated lakes filled, it might also be possible to distinguish the ages of the lowest and highest travertine deposits in each basin.

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References Cited

Benson, L., 2004, The Tufas of Pyramid Lake, Nevada: U.S. Geological Survey Circular 1267, 14 p.

Crossey, L.J., Fischer, T.P., Patchett, P.J., Karlstrom, K.E., Hilton, D.R., Newell, D.L., Huntoon, P., Reynolds, A.C., and de Leeuw, G.A.M., 2006, Dissected hydrologic system at the Grand Canyon: Interaction between deeply derived fl uids and plateau aquifer waters in modern springs and travertine: Geology, v. 4, p. 25–28, doi:10.1130/G22057.1.

Crossey, L.J., Karlstrom, K.E., Springer, A.E., Newell, D., Hilton, D.R., and Fischer, T., 2009, Degassing of mantle- derived CO2 and He from springs in the southern Colorado Plateau region—Neotectonic connections and implications for groundwater systems: Geological Society of America Bulletin, v. 121, p. 1034–1053, doi:10.1130/B26394.1.

Dorsey, R.J., O'Connell, B., Homan, M., and Howard, K., 2016, Upper Limestone of the Southern Bouse Formation: Evidence for Unsteady Origins of the Colorado River: Short Paper for 2016 Desert Symposium Volume.

Dunn, J.R., 1953, The origin of the deposits of tufa in Mona Lake: Journal of Sedimentary Petrology: v. 23, p. 18-23.

Ford, T.D., and Pedley, H.M., 1996, A review of tufa and travertine deposits of the world: Earth-Science Reviews, v. 41, p. 117–175, doi:10.1016/S0012-8252(96)00030-X.

Gootee, B.F., et al. 2016. A sequence-stratigraphic interpretation of the upper bioclastic unit capping the Bouse Formation in the Cibola Area, Arizona and California (this volume)

McDougall, K., and Miranda Martínez, A.Y., 2014, Evidence for a marine incursion along the lower Colorado River corridor: Geosphere, v. 10, p. 842-869, doi:10.1130/GES00975.1.

Miller, D.M., Reynolds, R.E., Bright, J.E., Starratt, S.W., 2014, Bouse Formation in the Bristol basin near Amboy, California, USA: Geosphere, v. 10, p. 462-475, doi:10.1130/GES00934.1.

Pearthree, P.A., and House, P.K., 2014, Paleogeomorphology and evolution of the early Colorado River inferred from relationships in Mohave and Cottonwood valleys, Arizona, California, and Nevada: Geosphere, v. 10, p. 1139-1160, doi:10.1130/GES00988.1.

Pentecost, A., 2005, Travertine: Berlin, Springer Verlag, 445 p

Scholl, D.W. and Taft, W.H., 1964, Algae, contributions to the formation of calcareous tufa, Mono Lake, California: Journal of Sedimentary Petrology: v. 34, p. 309-319.

Spencer, J.E., Patchett, P.J., Pearthree, P.A., House, P.K., Sarna-Wojcicki, A.M., Wan, E., Roskowski, J.A., Faulds, J.E., 2013, Review and analysis of the age and origin of the Pliocene Bouse Formation, lower Colorado River Valley, southwestern USA: Geosphere, v. 9, p. 444-459, doi:10.1130/GES00896.1.

Wolaver, B.D., Crossey, L.J., Karlstrom, K.E., Banner, J.L., Cardenas, M.B., Ojeda, C.G., Sharp, J.M., 2013, Identifying origins of and pathways for spring waters in a semiarid basin using He, Sr, and C isotopes: Cuatrociénegas Basin, Mexico: Geosphere 9 (1), 113-125