Stable oxygen ($\delta^{18}O$) isotope data from paired inorganic calcite and ostracode valve analyses suggest a lacustrine origin for the southern Bouse formation, southwestern AZ and southeastern CA

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ABSTRACT—The late Miocene–early Pliocene southern Bouse Formation contains a controversial record of either a marine inundation or a brackish terminal lake along the lower Colorado River corridor. The ostracode assemblages and $\delta^{18}O$ values in ostracode valve calcite from the lacustrine northern Bouse Formation and contested southern Bouse Formation were studied and compared to determine depositional environments. The expected fill-and-spill lacustrine origin for the northern Bouse Formation in Chemehuevi basin is supported by an abrupt ~8‰ (VPDB) decrease in the $\delta^{18}O$ values from micrite and associated Candona spp. (fresh-brackish water ostracode) valve calcite, as closed-basin conditions were replaced by open-basin conditions. The $\delta^{18}O$ values in co-occurring Cyprideis sp. (marginal marine ostracode) and Candona spp. valves in the southern Bouse Formation are very similar to each other and they are nearly identical to the $\delta^{18}O$ values in Candona spp. valves from the northern Bouse Formation, indicating the ostracodes in both basins calcified in similar freshwater to brackish environments. An identical, abrupt shift from high to much lower $\delta^{18}O$ values in Cyprideis sp. and Candona spp. valves is also observed in the southern Bouse Formation, suggesting a similar fill-and-spill lacustrine environment. The $\delta^{18}O$ values in micrite and in Cyprideis spp. valves from two southern Bouse Formation outcrops located at the northern and southern margins of Blythe basin and separated by nearly 100 km are nearly identical, and are incompatible with a marine or an estuarine interpretation. The $\delta^{18}O$ values in micrite and ostracode valves from the lacustrine northern Bouse Formation and southern Bouse Formation are similar, both in discrete values and in stratigraphic context. This similarity suggests that the southern Bouse Formation is lacustrine in origin.

Introduction

Ever since John Wesley Powell’s historic journey through the Grand Canyon in 1869, the Colorado River has been an iconic symbol of the American Southwest. It is the largest river in the southwestern United States, flowing over 2,300 km from its headwaters in the Rocky Mountains in Colorado to the Gulf of California, and draining over 600,000 square kilometers of watershed (Blinn and Poff, 2005). The evolution of the modern Colorado River is more fascinating than even Powell could have imagined.

Prior to about 15 Ma, watersheds in the southwestern U.S. flowed generally to the north or northwest (e.g., Cather et al., 2012). Between about 15 Ma and 6 Ma, extension and subsidence in the Basin and Range Province of the western U.S. and the opening of the Gulf of California caused wholesale reorganization of southwestern U.S. watersheds (Potochnik and Faulds 1998; Potochnik, 2001; Cather et al., 2012; Dickinson, 2015). Shortly after 6 Ma, exotic river gravels carried by a developing Colorado River appeared for the first time to the west of the modern Grand Canyon (Lucchitta,
1972; Spencer et al., 2001). After turning to the south near Las Vegas, NV (Fig. 1), the developing Colorado River had to work its way across a tectonically chaotic landscape of internally drained basins (e.g., Faulds et al., 2008; Kimbrough et al., 2015) before finally reaching the early Gulf of California at about 5.3 Ma (Dorsey et al., 2007, 2011). The sequence of events and individual processes that forged the course of the modern Colorado River through the Grand Canyon are passionately debated (e.g., Meek and Douglas, 2001; Pederson, 2008; Wernicke, 2011; Dickinson, 2013; Karlstrom et al., 2014), as are the interpretations of the events that led to the lower Colorado River finally reaching the Gulf of California (e.g., Smith, 1970; Lucchitta, 1979; Spencer and Patchett, 1997; House et al., 2008; McDougall and Miranda Martinez, 2014; Bright et al., in press).

An enigmatic series of ~ 5 Ma carbonate and siliciclastic deposits that are discontinuously exposed along nearly 250 km of the lower Colorado River corridor between Las Vegas, NV, and Yuma, AZ, (Fig. 1) preserve a record of the events that happened before the lower Colorado River became fully integrated with the Gulf of California. This suite of sediments has been named the Bouse Formation (Metzger, 1968). Since the early 1900s, the origin of the Bouse Formation has been the focus of considerable debate. Early workers found fossil clams, barnacles, and foraminifers in the southernmost exposures of the Bouse Formation, in what is now Blythe basin (hereafter “southern Bouse Formation”) (Fig. 1). Initial interpretations accounted for the marine fossil assemblage by suggesting that the southern Bouse Formation was deposited in a northern embayment or estuary of the early Gulf of California (Ross, 1923; Brown, 1923; Noble, 1931, Wilson, 1931; Smith, 1970). Blair and Armstrong (1979) later suggested that the unfossiliferous Bouse Formation exposed north of Blythe basin (hereafter “northern Bouse Formation”) should also be included in the marine transgression model in order to accommodate similar limestones that are exposed almost as far north as Las Vegas, NV (Fig. 1). The marine interpretation has been expanded on and reinforced by several more recent studies that have since confined the proposed marine influence to Blythe basin (McDougall, 2008; Miller et al., 2014; McDougall and Miranda Martinez, 2014). The recognition of a variety of planktic foraminifers, plus nearly 25 additional species of benthic foraminifers, as well as a diverse assemblage of marine diatoms, in the southern Bouse Formation strongly supports a marine interpretation (Smith, 1970; McDougall and Miranda Martinez, 2014; Miller et al., 2014).

Hamilton (1960) was the first to propose an alternative interpretation favoring a saline lake origin for the southern Bouse Formation. The notion that lakes may have played a pivotal role in the evolution of the Colorado River corridor has been expanded on over the past 50 years (e.g., Blackwelder, 1964; Meek and Douglas, 2001; House et al., 2008). A number of
studies focusing on paleontology, geomorphology, and on both stable isotope ($\delta^{18}O$, $\delta^{13}C$) values and strontium isotope ratios ($^{87}Sr/^{86}Sr$) in northern Bouse Formation carbonates (Fig. 1) collectively suggest deposition in a series of southward cascading, fresh to mildly brackish lakes that were fed by the ancestral Colorado River (Spencer and Patchett, 1997; Poulson and John, 2003; House et al., 2008; McDougall, 2008; Reynolds and Berry, 2008; Roskowski et al., 2010; Pearthree and House, 2014; Crossey et al., 2015).

Southern Bouse Formation carbonates have $\delta^{18}O$ and $\delta^{13}C$ values and $^{87}Sr/^{86}Sr$ ratios that overlap those of the northern Bouse Formation (Spencer and Patchett, 1997; Poulson and John, 2003, Crossey et al., 2015), permitting a similar ancestral Colorado River-fed lake origin. Geochemical evidence for a marine origin, such as marine $^{87}Sr/^{86}Sr$ ratios, has not been found (Spencer and Patchett, 1997; Roskowski et al., 2010; Crossey et al., 2015). However, the strontium provenance dynamics of the ~ 5 Ma lower Colorado River corridor, and in Blythe basin in particular, are surprisingly complex (Crossey et al., 2015). Groundwater with high strontium concentrations and continental $^{87}Sr/^{86}Sr$ ratios were present in the area just before the southern Bouse Formation was deposited. A small contribution of this groundwater could produce the continental $^{87}Sr/^{86}Sr$ ratios of the southern Bouse Formation even if 25–75% of the water in Blythe basin was seawater (Crossey et al., 2015).

The proximity of Blythe basin to seawater at ~ 5 Ma is not contested (Fig. 1). Miocene marine rocks underlie proposed Bouse Formation sediments in wells near Yuma, AZ (Fig. 1) just 60 km south of Blythe basin (Olmstead et al., 1973; McDougall, 2008). The geochemical and paleontologic characteristics of the southern Bouse Formation appear to be discordant, or even incompatible, thus the origin of the southern Bouse Formation and its marine fauna is intensely debated (e.g. Spencer et al., 2013; McDougall and Miranda Martinez, 2014). It is still unclear whether or not seawater from the early Gulf of California extended into Blythe basin. This question is the focus of our investigation.

**Significance**

Whether the southern Bouse Formation is marine or lacustrine has implications for our understanding of both the regional post-Miocene tectonic history of the lower Colorado River corridor, and the biogeography of a diverse marine assemblage in what may be a continental lake setting. Outcrops of the southern Bouse Formation are found as high as 330 masl (Pearthree and House, 2014) (Fig. 1). If the southern Bouse Formation was originally deposited at sea level as either a marine or estuarine deposit, then its current elevation requires significant post-Miocene uplift, which has larger implications for the tectonic evolution of southwestern Arizona and southeastern California (e.g., Dorsey and Langenheim, 2015) and for the rate and timing of uplift of the neighboring Colorado Plateau (Lucchitta, 1979). If the southern Bouse Formation is lacustrine, then the elevation of the outcrops simply reflects water level within a closed basin and significant post-Miocene uplift is not explicitly required to explain the basin’s current elevation (Spencer and Patchett, 1997).

The second key topic is the diversity of nominally marine fossils in the southern Bouse Formation, which is highly unusual for a lake. The marine fossils can be easily accounted for by a marine or estuarine interpretation. However, marine mollusks, benthic foraminifers, and more rarely barnacles, have been documented in lakes (Anadón, 1992). A modern lacustrine analog might be found in the land-locked Salton Sea (Fig. 1), which contains an impressive variety of marine organisms, including nearly 20 species of benthic foraminifers (Arnal, 1958; Whistler, 1995), an unexpected variety of marine diatoms (Lange and Tiffany, 2002), the barnacle *Balanus amphitrite* (Detwiler et al., 2002), as well as numerous other typically marine organisms (Detwiler et al., 2002). However, to our knowledge, there are no examples of a lake fauna that includes uncontested occurrences of planktic foraminifers (e.g., McDougall and Miranda Martinez, 2014).

**Methods and rationale**

One outcrop of northern Bouse Formation from Chemehuevi basin and two outcrops of southern Bouse Formation from Blythe basin were strategically selected along a north-south transect (Fig. 1) and sampled for stable oxygen isotope ($\delta^{18}O$) analyses of both fine grained (< 45 μm) micrite and the associated ostracode valves. Outcrops of southern Bouse Formation were sampled near Parker, AZ, and along Hart Mine Wash, AZ (Fig. 1). The outcrop at Parker is located near where the developing Colorado River presumably would have entered Blythe basin (Fig. 1). The outcrop at Hart Mine Wash is located near the southern margin of Blythe basin (Fig. 1), far from any major river input, and would have been near the mouth of the proposed Bouse estuary.
This sampling strategy allows for the comparison of δ¹⁸O values in micrite and ostracode calcite from a lacustrine environment in Chemehuevi basin against similar material from the contested southern Bouse Formation exposed at Parker and at Hart Mine Wash.

If the southern Bouse Formation is marine, then the micrite and ostracode δ¹⁸O values from Parker and Hart Mine Wash should be similar to each other and should have δ¹⁸O values characteristic of marine carbonates, and southern Bouse Formation δ¹⁸O values should be distinguishable from δ¹⁸O values from the lacustrine northern Bouse Formation. Similarly, if the southern Bouse Formation is estuarine, then the micrite and ostracode δ¹⁸O values should show a transition from lacustrine conditions in Chemehuevi basin, to dilute marine conditions at the head of the Bouse estuary near Parker, to nearly normal marine conditions near the mouth of the Bouse estuary near Hart Mine Wash, located nearly 100 km south of Parker (Fig. 1). Specifically, salinity and water δ¹⁸O values in estuaries are positively correlated as saline marine water with high δ¹⁸O values mixes with dilute river water with low δ¹⁸O values (e.g., Ingram, 1996). If the southern Bouse Formation is estuarine, then there should be a noticeable increase in micrite and ostracode δ¹⁸O values from the head of the proposed estuary at Parker to the mouth of the estuary near Hart Mine Wash.

Bouse Formation sediments were disaggregated and sieved over 45 μm screens. Microfauna in the > 120 μm fraction were identified and counted. A portion of the < 45μm sediment fraction (micrite) was retained, dried at 40°C, and analyzed for its δ¹⁸O values (δ¹⁸O_MIC). Valves from two co-occurring genera of ostracodes (Cyprideis – marginal marine but continentally invasive ostracode; Candona – fresh to brackish water continental ostracode) were also analyzed for their δ¹⁸O values (δ¹⁸O_CYP, δ¹⁸O_CAN, respectively). All δ¹⁸O values were generated using an automated KIEL-III carbonate preparation device attached to a Finnegan MAT 252 gas-ratio mass spectrometer and the University of Arizona. The stable isotope results are reported in standard delta (δ) notation where: δ‰ = [(R_sample / R_std )-1] x 103; and R = ratio of ¹⁸O:¹⁶O. R_std refers to the standard Vienna Peeedee belemnite (VPDB).

### Preliminary results

#### Chemehuevi basin

The northern Bouse Formation in Chemehuevi basin (Fig. 1; 34.4477° N, 114.4010° W, 150 masl) consists of about 0.1 m of pale green clay that overly coarse sands and pebbles (Fig. 2). The initial green clay is overlain by about 5 meters of carbonate-rich marly sediments that are in turn overlain by about 2 meters of dense green claystone (Fig. 2). Roughly 6 meters of sand overlie the green claystone (Fig. 2). The sand is finally overlain by about 2 meters of brown, shaley claystone (Fig. 2).

The micrite from roughly the lowest 2 meters of marly sediments have an expectedly low, non-marine δ¹⁸O_MIC value (-14 ± 1‰; Fig. 3). This suggests that open-basin conditions prevailed when those sediments were deposited. Associated valve fragments from the freshwater ostracode Candona spp. have a surprisingly high δ¹⁸O_CAN value (-1 ± 1‰; Fig. 3). The offset between the δ¹⁸O_MIC and δ¹⁸O_CAN values in the Chemehuevi section can be accounted for by various combinations of a +2‰ vital effect in δ¹⁸O_CAN values (von Grafenstein et al., 1999), a temperature contrast between the epilimnion where the micrite formed and the benthos where the Candona spp. valves were calcified (~ +0.24‰ per 1° C cooling; e.g., Leng and Marshall, 2004), and perhaps mild seasonal isotopic stratification between the epilimnion and benthos. A δ¹⁸O_CAN value close to 0‰ could be interpreted as “marine-like”.

However, Candona spp. are continental ostracodes and are unknown from normal seawater environments, so a normal marine origin is highly unlikely. A lacustrine origin for the high δ¹⁸O_CAN value is supported by equally high δ¹⁸O_CAN values from the fully lacustrine Lake Bonneville sequence in Utah (J. Oviatt, pers. comm.), and from closed-basin conditions at Lake Villarroya, Spain (Anadón et al., 2008)

The upper two thirds of the marly sediments, the green clays, and the brown shales contain micrite with a much lower δ¹⁸O_MIC value (-14 ± 1‰; Fig. 3). This suggests that open-basin conditions prevailed when those sediments were deposited. Associated valve fragments of Candona sp. from the upper carbonate-rich sediments and green claystone also have much lower δ¹⁸O_CAN values (-9 ± 1‰; Fig. 3). The transition from comparatively high δ¹⁸O_MIC and δ¹⁸O_CAN values near the base of the section to much lower δ¹⁸O_MIC and δ¹⁸O_CAN values in the upper two thirds of the section likely represents the initial closed-basin filling of Chemehuevi basin with evaporatively ¹⁸O-enriched water sourced from the much larger Mohave basin to the north (Fig. 1).
followed by a transition to a through-flowing, open basin configuration as Chemehuevi basin filled and finally over-spilled. A nearly identical isotopic transition has been reported from Lake Villarroya, Spain, when it converted from a brackish closed-basin environment to an over-spilling lacustrine and paludal environment (Anadón et al., 2008). Our interpretation of the Chemehuevi basin isotope data is consistent with the “fill-and-spill” lacustrine model for northern Bouse Formation (e.g., House et al., 2008; Pearthree and House, 2014).

**Blythe basin**

The southern Bouse Formation sediments at Parker (Fig. 1; 39.1623° N 114.3021° W, 116 masl) consist of a thin bioclastic carbonate horizon of variable thickness (0.3 – 0.7 m) that is overlain by about 1.5 meters of soft marl, and then several meters (unmeasured) of dense green claystone (Fig. 2). The bioclastic carbonate was sampled three times, the soft marl was sampled at about 10 cm intervals, and the lowest 1.5 m of the green claystone was sampled four times (Fig. 2). At Hart Mine Wash (Fig. 1; ~ 33.2926° N, 114.6320° W, 110 to 135 masl), the sedimentary package is much thicker (Fig. 2). The basal bioclastic carbonate and resistant marl horizon can be as much as 5 m thick. The overlying soft marl is about 10 m thick. The marl is then overlain by about 2 m of green claystone (Fig. 2), which in turn, is overlain by about 20 m of red clays, silts, and fine sands. Only the initial ~ 1 meter of the red silts and clays are depicted in Figure 2. At Hart Mine Wash, a distinctive clay layer (DCL) occurs about 1 m below the marl-green clay contact (Fig. 2). The roughly 1 meter of marl above the DCL and the overlying siliciclastic sediments are included in the “interbedded unit” of Metzger (1968) and Homan (2014). The DCL was not found at Parker. The bioclastic limestone at Parker and Hart Mine Wash was likely deposited in a near-shore environment whereas the soft marl and green claystone were deposited in deeper, quieter water (e.g., Homan, 2014).

The δ18O MIC values from valves of the marginal marine but continentally invasive ostracode *Cyprideis* sp. (δ18O CYP ) recovered from the bioclastic carbonate at both Parker and Hart Mine Wash are surprisingly similar, and they are much lower than what is expected from a marine environment (Fig. 3). The δ18O MIC values in the soft marl at Parker and in the soft marl below the DCL at Hart Mine Wash are also fairly similar, and again both are much lower than what is expected from a marine environment (Fig. 3). The δ18O MIC values in the soft marl at Parker and in the soft marl below the DCL at Hart Mine Wash are also fairly similar, and again both are much lower than what is expected from a marine environment (Fig. 3). The δ18O MIC values in the soft marl at Parker and in the soft marl below the DCL at Hart Mine Wash are also fairly similar, and again both are much lower than what is expected from a marine environment (Fig. 3).
similar, at about -3‰ (Fig. 3). Such high δ¹⁸O values might suggest a marine origin, but Candona spp. are unknown from normal seawater environments and the ostracode δ¹⁸O values of about -3‰ are surprisingly similar to the δ¹⁸O_MIC values from the lower lacustrine marls at Chemehuevi (Fig. 3). The known ecology of Candona spp. and the similarity in δ¹⁸O_MIC values from Chemehuevi and the δ¹⁸O_CYP and δ¹⁸O_CAN values from Parker and Hart Mine Wash outcrops argue against a marine or an estuarine interpretation for the southern Bouse Formation.

The δ¹⁸O_MIC values from the post-DCL marl at Hart Mine Wash are similar to the δ¹⁸O_MIC values from the pre-DCL marl there (Fig. 3), but the δ¹⁸O_CYP and δ¹⁸O_CAN values in the post-DCL marl are about 7%o to 10%o lower than the δ¹⁸O_CYP and δ¹⁸O_CAN values from the pre-DCL marls (Fig. 3). The details of the abrupt decrease in ostracode δ¹⁸O values across the DCL are discussed in detail in Bright et al. (in press). Briefly, the DCL likely marks a significant change in the hydrology and isotope systematics of the water mass that inundated Blythe basin. We interpret this abrupt change as a transition from closed-basin to open-basin lacustrine conditions (Bright et al., in press), similar to that seen in Chemehuevi basin (this study) and in Lake Villarroya, Spain (Anadón et al., 2008).

And finally, the stratigraphic structure of the δ¹⁸O_MIC values and δ¹⁸O_OST values from the lacustrine northern Bouse Formation is largely replicated at both Parker and in the sediments at Hart Mine Wash (Fig. 3). Note that the lowest sediments exposed at Chemehuevi and Parker contain micrite with moderate non-marine δ¹⁸O_MIC values which are then overlain by marls with much lower δ¹⁸O_MIC values (Fig. 3). This up-section decrease in δ¹⁸O_MIC values seems curious if the initial sediments, especially in Blythe basin, were deposited in normal seawater. Note that the near-shore, bioclastic carbonate at Parker and Hart Mine Wash contain ostracodes with moderate, non-marine δ¹⁸O_OST values but that the overlying deeper water marls at both locations contain ostracodes with much higher δ¹⁸O_OST values (Fig. 3). The up-section increase in δ¹⁸O_OST values is
largely the opposite of what is observed for the associated δ¹⁸O_MIC values (Fig. 3), and is again curious if the initial sediments deposited in Blythe basin were deposited in a marine environment. And finally, note that the large, nearly 8‰, decrease in the δ¹⁸O_OST values in the lacustrine Chemehuevi section is replicated across the DCL at Hart Mine Wash (Fig. 3). It seems implausible that such a similar isotopic signal would occur in two adjacent basins, where one basin is dominated by lacustrine processes and the other basin is dominated by estuarine or marine processes. Collectively, the similarity in δ¹⁸O_MIC and δ¹⁸O_OST values throughout all three outcrops, both in magnitude and in stratigraphic structure, suggests that the southern Bouse Formation is lacustrine in origin.

Conclusions

There is no appreciable difference in the δ¹⁸O_MIC or δ¹⁸O_OST values from the lacustrine northern Bouse Formation sediments exposed in Chemehuevi basin and from the contested southern Bouse Formation sediments exposed at Parker and Hart Mine Wash. The δ¹⁸O_MIC values from Parker and Hart Mine Wash are too low to represent calcification in normal seawater; a marine interpretation for the southern Bouse Formation seems untenable. There is no appreciable difference in the δ¹⁸O_MIC or δ¹⁸O_OST values from Parker and Hart Mine Wash; an estuarine interpretation seems untenable. The δ¹⁸O_OST values in both basins abruptly decrease by ~8‰, suggesting a significant, and similarly abrupt, change in hydrology occurred in both basins. The similarity in the δ¹⁸O_MIC and δ¹⁸O_OST values, coupled with the similarities in isotopic stratigraphy, at all three Bouse Formation outcrops favor a lacustrine origin for the southern Bouse Formation.

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