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 wholescale 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,

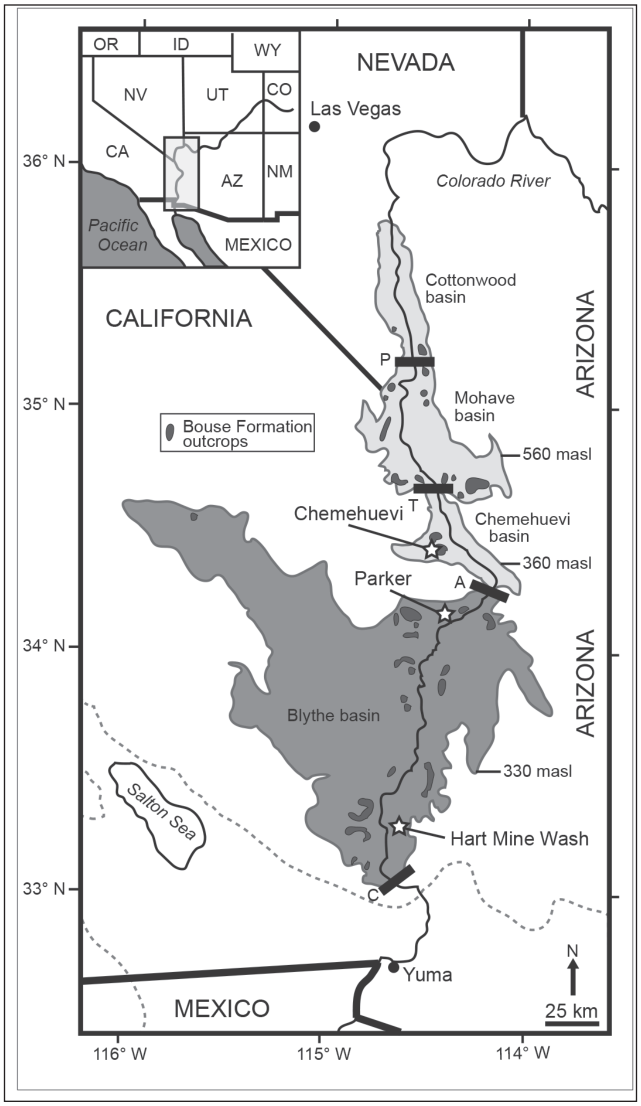

Figure 1. Regional map showing the relationship between the course of the modern lower Colorado River, the contested marine or lacustrine Blythe basin (dark grey), the uncontested lacustrine basins (light grey), proposed paleodams (black bars with letters), and our study locations (white stars). Numbers adjacent to each basin outline represents the highest known elevation of Bouse Formation in each respective basin. Dashed grey line estimates the area of the Salton Trough that would be flooded by seawater if the landscape was lowered by 330 m. P – Pyramid; T – Topock; A – Aubrey; C – Chocolate. Inset map shows the location of the lower Colorado River corridor (grey box) in relation to the southwestern U.S. Main figure based on Pearthree and House (2014)

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 $\delta^{18}O$ 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 $\delta^{18}O$ values from Parker and Hart Mine Wash should be similar to each other and should have $\delta^{18}O$ values characteristic of marine carbonates, and southern Bouse Formation $\delta^{18}O$ values should be distinguishable from $\delta^{18}O$ values from the lacustrine northern Bouse Formation. Similarly, if the southern Bouse Formation is estuarine, then the micrite and ostracode $\delta^{18}O$ 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 $\delta^{18}O$ values in estuaries are positively correlated as saline marine water with high $\delta^{18}O$ values mixes with dilute river water with low $\delta^{18}O$ values (e.g., Ingram, 1996). If the southern Bouse Formation is estuarine, then there should be a noticeable increase in micrite and ostracode $\delta^{18}O$ 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 $\delta^{18}O$ values ($\delta^{18}O_{MIC}$). 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 $\delta^{18}O$ values ($\delta^{18}O_{CYP}$, $\delta^{18}O_{CAN}$, respectively). All $\delta^{18}O$ 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: d‰ = $[(R_{SAMPLE}/R_{std})-1]$ x 103; and R = ratio of ^{18}O:^{16}O. R_{std} refers to the standard Vienna Peedee 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 $\delta^{18}O_{MIC}$ value (-7 ± 1‰; Fig. 3). In contrast, associated valve fragments from the freshwater ostracode *Candona* spp. have a surprisingly high $\delta^{18}O_{CAN}$ value (-1 ± 1‰; Fig. 3). The offset between the $\delta^{18}O_{MIC}$ and $\delta^{18}O_{CAN}$ values in the Chemehuevi section can be accounted for by various combinations of a +2‰ vital effect in $\delta^{18}O_{CAN}$ 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 $\delta^{18}O_{CAN}$ 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 $\delta^{18}O_{CAN}$ value is supported by equally high $\delta^{18}O_{CAN}$ 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 $\delta^{18}O_{MIC}$ 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 $\delta^{18}O_{CAN}$ values (-9 ± 1‰; Fig. 3). The transition from comparatively high $\delta^{18}O_{MIC}$ and $\delta^{18}O_{CAN}$ values near the base of the section to much lower $\delta^{18}O_{MIC}$ and $\delta^{18}O_{CAN}$ values in the upper two thirds of the section likely represents the initial closed-basin filling of Chemehuevi basin with evaporatively ^{18}O-enriched water sourced from the much larger Mohave basin to the north (Fig. 1),

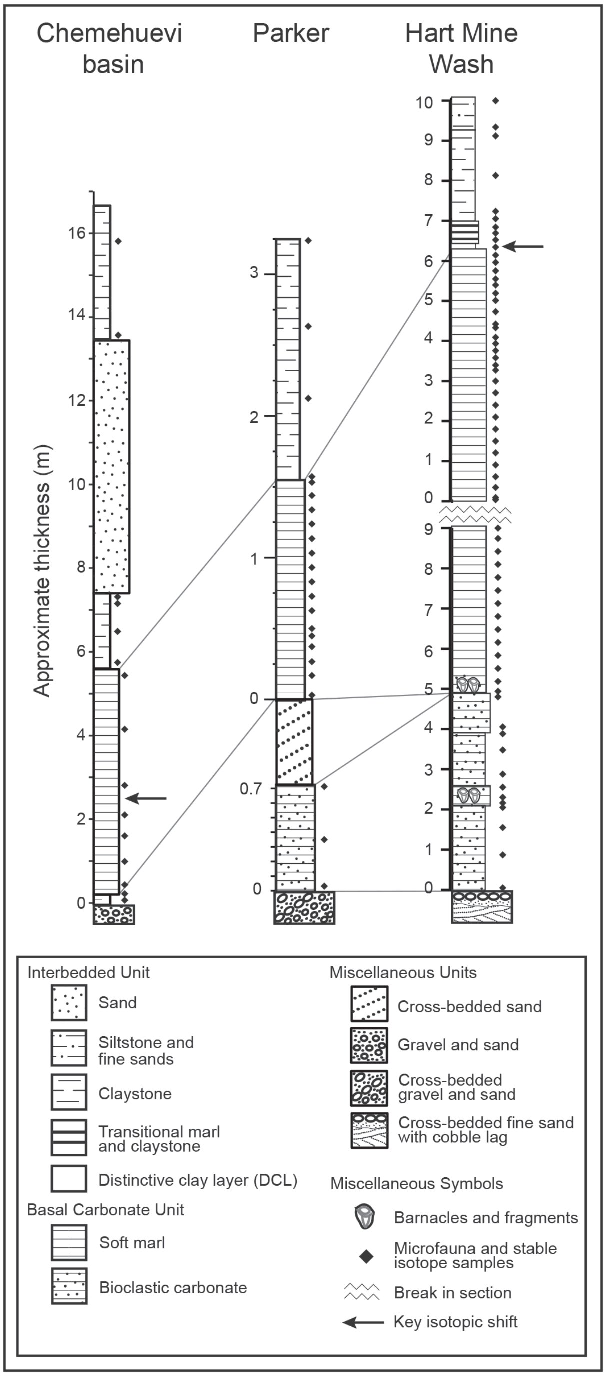

Figure 2. Stratigraphic sections of the northern Bouse Formation sediments in Chemehuevi basin and southern Bouse Formation sediments at Parker and Hart Mine Wash featured in this study (see Fig. 1 for locations). Note the difference in vertical scale for each stratigraphic section.

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 $\delta^{18}O_{MIC}$ and $\delta^{18}O$ values from valves of the marginal marine but continentally invasive ostracode *Cyprideis* sp. ($\delta^{18}O_{CYP}$) 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 $\delta^{18}O_{MIC}$ 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 would be expected if the micrite was formed in seawater (Fig. 3). The similarity in $\delta^{18}O_{MIC}$ values over 100 km apart is also unexpected if the micrite was deposited near the head (Parker) and near the mouth (Hart Mine Wash) of an estuary. Notably, the $\delta^{18}O_{CYP}$ values from the soft marl at Parker and both the $\delta^{18}O_{CYP}$ and $\delta^{18}O_{CAN}$ values from the pre-DCL marl at Hart Mine Wash are

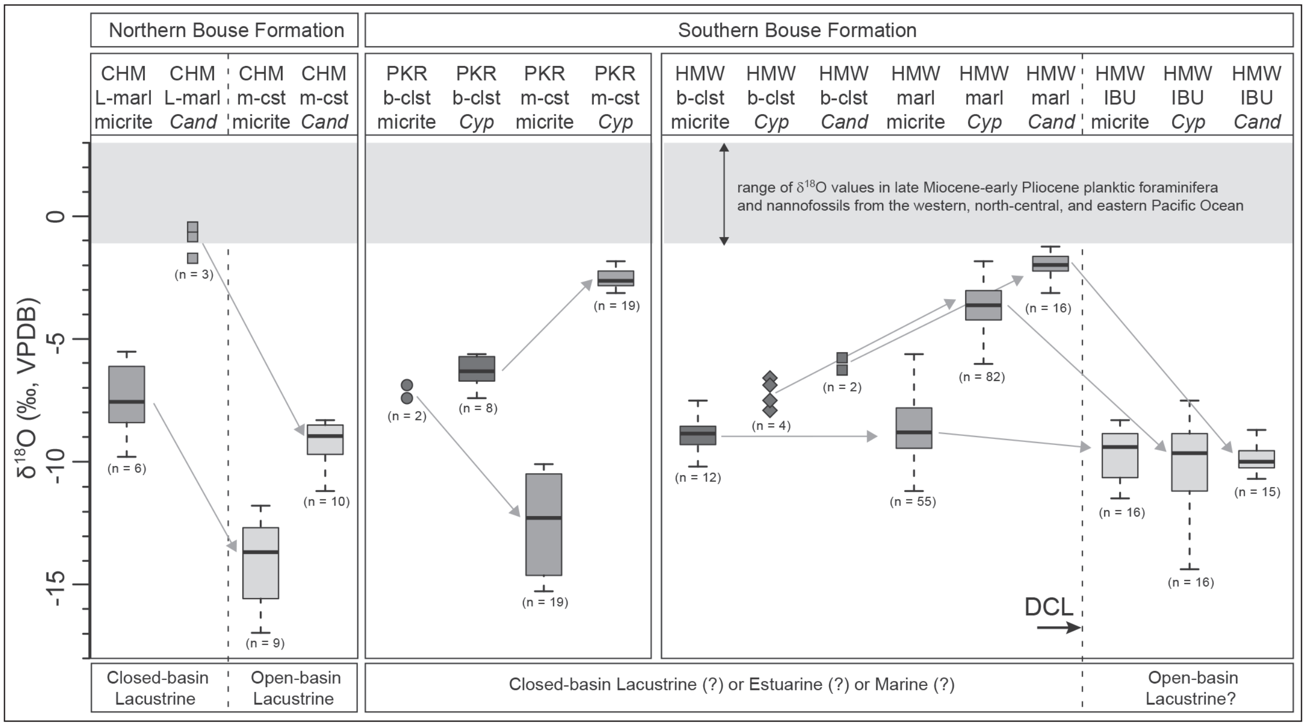

Figure 3. Box-and-whisker plots of d18O values from micrite and ostracode valves from the northern Bouse Formation in Chemehuevi basin (CHM) and the southern Bouse Formation at Parker (PKR) and Hart Mine Wash (HMW). L-marl – lower marl; m-cst – upper marl and green claystone; b-clst – bioclastic carbonate; marl – soft marl; IBU – Interbedded Unit; Cyp – *Cyprideis* sp. (marginal marine but continentally invasive ostracode); Cand – *Candona* spp. (continental fresh to brackish water ostracode); colored boxes – upper and lower quartiles; thick black horizontal line – median; whiskers – 1.5 x interquartile range. Outliers that exceed 1.5 x interquartile range (n = 10) are excluded for clarity. Samples that have four or less results are represented by individual symbols. Squares – *Candona* spp., circles – micrite from bioclastic horizon, diamonds – *Cyprideis* sp. The range of $\delta^{18}O$ values for late Miocene–early Pliocene uncontested marine carbonate from the Pacific Ocean is derived from Douglas and Savin (1971, 1975, 1978), Keigwin (1979, 1982), Barrera et al. (1985), Cannariato and Ravelo (1997), and Prokoph et al. (2008).

similar, at about -3‰ (Fig. 3). Such high $\delta^{18}O$ values might suggest a marine origin, but *Candona* spp. are unknown from normal seawater environments and the ostracode $\delta^{18}O$ values of about -3‰ are surprisingly similar to the $\delta^{18}O_{CAN}$ values from the lower lacustrine marls at Chemehuevi (Fig. 3). The known ecology of *Candona* spp. and the similarity in $\delta^{18}O_{CAN}$ values from Chemehuevi and the $\delta^{18}O_{CYP}$ and $\delta^{18}O_{CAN}$ values from Parker and Hart Mine Wash outcrops argues against a marine or an estuarine interpretation for the southern Bouse Formation.

The $\delta^{18}O_{MIC}$ values from the post-DCL marl at Hart Mine Wash are similar to the $\delta^{18}O_{MIC}$ values from the pre-DCL marl there (Fig. 3), but the $\delta^{18}O_{CYP}$ and $\delta^{18}O_{CAN}$ values in the post-DCL marl are about 7‰ to 10‰ lower than the $\delta^{18}O_{CYP}$ and $\delta^{18}O_{CAN}$ values from the pre-DCL marls (Fig. 3). The details of the abrupt decrease in ostracode $\delta^{18}O$ 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 $\delta^{18}O_{MIC}$ values and $\delta^{18}O_{OST}$ 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 $\delta^{18}O_{MIC}$ values which are then overlain by marls with much lower $\delta^{18}O_{MIC}$ values (Fig. 3). This up-section decrease in $\delta^{18}O_{MIC}$ 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 $\delta^{18}O_{OST}$ values but that the overlying deeper water marls at both locations contain ostracodes with much higher $\delta^{18}O_{OST}$ values (Fig. 3). The up-section increase in $\delta^{18}O_{OST}$ values is largely the opposite of what is observed for the associated $\delta^{18}O_{MIC}$ 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 $\delta^{18}O_{OST}$ 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 $\delta^{18}O_{MIC}$ and $\delta^{18}O_{OST}$ 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 $\delta^{18}O_{MIC}$ or $\delta^{18}O_{OST}$ 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 $\delta^{18}O_{MIC}$ 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 $\delta^{18}O_{MIC}$ or $\delta^{18}O_{OST}$ values from Parker and Hart Mine Wash; an estuarine interpretation seems untenable. The $\delta^{18}O_{OST}$ 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 $\delta^{18}O_{MIC}$ and $\delta^{18}O_{OST}$ 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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