Review and analysis of the age and origin of the Pliocene Bouse Formation, lower Colorado River Valley, southwestern USA

Jon E. Spencer1,*, P. Jonathan Patchett2,*, Philip A. Pearthree1,*, P. Kyle House3,*, Andrei M. Sarna-Wojcicki4,*, Elmira Wan5,*, Jennifer A. Roskowski6,*, and James E. Faulds7,*
1Arizona Geological Survey, 416 W. Congress Street, #100, Tucson, Arizona 85704, USA
2Emeritus, Department of Geosciences, University of Arizona, 1040 E 4th Street, Tucson, Arizona 85721, USA
3U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, Arizona 86001, USA
4Emeritus, U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA
5U.S. Geological Survey, 345 Middlefield Road, Menlo Park, California 94025, USA
6Department of Geosciences, University of Arizona, 1040 E 4th Street, Tucson, Arizona 85721, USA
7Nevada Bureau of Mines and Geology, Mackay School of Earth Sciences and Engineering, University of Nevada, Reno, Nevada 89557, USA

ABSTRACT

The lower Pliocene Bouse Formation in the lower Colorado River Valley (southwestern USA) consists of basin marl and dense tufa overlain by siltstone and fine sandstone. It is locally overlain by and interbedded with sands derived from the Colorado River. We briefly review 87Sr/86Sr analyses of Bouse carbonates and shells and carbonate and gypsum of similar age east of Las Vegas that indicate that all of these strata are isotopically similar to modern Colorado River water. We also review and add new data that are consistent with a step in Bouse Formation maximum elevations from 330 m south of Topock Gorge to 555 m to the north. New geochemical data from glass shards in a volcanic ash bed within the Bouse Formation, and from modern Colorado River water. We first briefly review outcrop elevations, Sr isotopic data, and stratigraphy that support a lacustrine origin for the Bouse Formation with Sr isotopic evidence (Spencer and Patchett, 1997; Poulsen and John, 2003; Roskowski et al., 2010), consistent maximum elevations of Bouse deposits within proposed paleolake basins (Spencer et al., 2008a), and sedimentological evidence of floodwater influx derived from northern sources immediately preceding Bouse deposition in the northern Mohave Valley (House et al., 2005, 2008). A marine origin is supported by the presence of three marine species represented by fossils from low elevations in the axis of the Blythe Basin, which is the southernmost of the Bouse basins (Smith, 1970; Todd, 1976; Crabtree, 1989; McDougall, 2008). In addition, some sedimentological features have been interpreted to indicate an estuarine origin (Buisin, 1990; Turak, 2000). If deposition of the Bouse Formation resulted from the first arrival of Colorado River water to the Basin and Range province, then it marks the initiation of a new river and incision of the modern Grand Canyon along its course (Spencer et al., 2008b). In the estuary interpretation, the Bouse Formation records a phase of subsidence associated with early rifting in the Gulf of California that is not obviously or necessarily related to Colorado River arrival and initiation of incision of the Grand Canyon.

INTRODUCTION

The lower Pliocene Bouse Formation, located in the lower Colorado River trough of southeastern California, western Arizona, and southernmost Nevada (United States), consists typically of 1–10 m of limestone overlain conformably by siltstone and fine sandstone that are in turn overlain by Colorado River sand and gravel or alluvial fan sediments (Metzger et al., 1973; Metzger and Loeltz, 1973; Buising, 1990; Turak, 2000; House et al., 2005, 2008). The Bouse Formation was deposited on alluvial fan sediments, bedrock hillslopes, and in a few exposures, finer grained alluvial valley deposits, and represents inundation of a previously subaerial environment. Inundation has been attributed to regional subsidence resulting in marine incursion during early opening of the Gulf of California (Lucchitta, 1979; Buising, 1990), or to filling of closed basins by first-arriving Colorado River water (Spencer and Patchett, 1997; House et al., 2008; definition of “inundation” following Flick et al., 2012). A lacustrine origin is supported by Sr, O, and C isotopic evidence (Spencer and Patchett, 1997; Poulsen and John, 2003; Roskowski et al., 2010), consistent maximum elevations of Bouse deposits within proposed paleolake basins (Spencer et al., 2008a), and sedimentological evidence of floodwater influx derived from northern sources immediately preceding Bouse deposition in the northern Mohave Valley (House et al., 2005, 2008). A marine origin is supported by the presence of three marine species represented by fossils from low elevations in the axis of the Blythe Basin, which is the southernmost of the Bouse basins (Smith, 1970; Todd, 1976; Crabtree, 1989; McDougall, 2008). In addition, some sedimentological features have been interpreted to indicate an estuarine origin (Buisin, 1990; Turak, 2000). If deposition of the Bouse Formation resulted from the first arrival of Colorado River water to the Basin and Range province, then it marks the initiation of a new river and incision of the modern Grand Canyon along its course (Spencer et al., 2008b). In the estuary interpretation, the Bouse Formation records a phase of subsidence associated with early rifting in the Gulf of California that is not obviously or necessarily related to Colorado River arrival and initiation of incision of the Grand Canyon.

Footnotes:

*Emails: Spencer: jon.spencer@azgs.az.gov; Patchett: patchett@email.arizona.edu; Pearthree: phil.pearthree@azgs.az.gov; House: khouse@usgs.gov; Sarna-Wojcicki: asama@usgs.gov; Wan: ewan@usgs.gov; Roskowski: jen.roskowski@gmail.com; Faulds: jfaulds@unr.edu.

© 2013 Geological Society of America

For permission to copy, contact editing@geosociety.org

Geosphere: June 2013; v. 9; no. 3; p. 444–459; doi:10.1130/GES00896.1; 10 figures; 3 tables.
Received 1 January 2013 • Revision received 24 March 2013 • Accepted 27 March 2013 • Published online 16 May 2013

For permission to copy, contact editing@geosociety.org

© 2013 Geological Society of America

For permission to copy, contact editing@geosociety.org

© 2013 Geological Society of America

Downloaded from https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/9/3/444/3343521/444.pdf by guest
Colorado River Valley and within similar marl in Bristol Basin (Reynolds et al., 2008; Miller et al., 2012a) that indicate simultaneous submergence of several modern basins covering much of the southeastern Mojave Desert region. This ash bed was correlated with the 4.83 Ma Lawlor Tuff, which originated in the Sonoma volcanic field in northern California (Sarna-Wojcicki et al., 2011). Correlation to a dated ash bed thus dates Bouse inundation and, in our interpretation, approximately dates arrival of Colorado River water to the Mojave Desert region and the beginning of incision of the modern Grand Canyon. We then present results of numerical simulations of filling and spilling of formerly closed basins along the path of the lower Colorado River that include the Bristol Basin extension of Blythe Basin. These calculations are similar to those done in Spencer et al. (2008a), but yield slightly different results because of inclusion of Bristol Basin in the inundation area and a wider range of assumptions about the extent of upstream lakes in the modern Lake Mead region.

**BOUSE FORMATION AND RELATED UNITS**

The Bouse Formation is exposed at numerous localities along the lower Colorado River Valley south of Lake Mead and north of Yuma (Fig. 1; Metzger et al., 1973; Metzger and Loeltz, 1973; Buisin; 1988; House et al., 2008). It was largely buried by younger river and alluvial fan deposits, but Pliocene to Quaternary incision along the river valley produced numerous, widely scattered exposures. The Bouse Formation is also recognized in the subsurface from water-well drilling logs (although some of these identifications are uncertain). Abundant Bouse Formation exposures as identified by Metzger et al. (1973) and Metzger and Loeltz (1973) are almost entirely restricted to three basins along the Colorado River, each separated by a bedrock gorge where the Colorado River has incised a canyon between basins. From north to south, these are the “Mohave-Cottonwood Basin” (i.e., the combined Mohave Basin and Cottonwood Basin, which are divided by a set of low bedrock hills at Davis Dam; House et al., 2005, 2008) centered on Bullhead City, Havasu Basin centered on Lake Havasu City, and Blythe Basin in the Parker-Blythe-Cibola area (Fig. 1). Most basal Bouse exposures in all basins consist of hard, massive, dense (no pores), basal tufa where deposited on bedrock, and thin-bedded marl, bedded limestone, and bedded calcareous sandstone where deposited on alluvium. (Note that “tufa” rather than “tufa” was the term used by Hamilton [1960] to describe hard Bouse carbonates, and “tufa” is more consistent with modern usage and is consistent with the definition of Ford and Pedley [1996]). These calcareous strata are commonly overlain by mudstone and fine sandstone of variable thickness, ranging from <1 m to >65 m thick in outcrop. As much as 230 m of clastic Bouse deposits have been interpreted from well logs in Blythe Basin (Metzger et al., 1973). Generally, Bouse deposits are unconformably overlain by coarse alluvial fan deposits or Colorado River sand and gravel deposits, but in some areas fine-grained clastic Bouse deposits are interbedded with sand deposits apparently supplied by the Colorado River (Buisin, 1990). Tufa was probably deposited (or precipitated) in shallow-water, nearshore environments (Metzger, 1968; Buisin, 1990), and is found through a substantial altitudinal range, especially in the Blythe Basin.

![Figure 1. Map of the lower Colorado River Valley showing generalized locations of Bouse Formation outcrops and elevation (elev.) contours that represent maximum elevations of known exposures (Mts.—mountains). Also shown are interstate highways and towns along the Colorado River.](https://pubs.geoscienceworld.org/gsa/geosphere/article-pdf/9/3/444/3343321/444.pdf)

American Geological Institute *Glossary of Geology* definitions [Neuendorf et al., 2005, p. 683, described tufa as “spongy or less compact” than travertine]. We use the term “tufa” herein, however, because this is the dominant historical usage and is consistent with the definition of Ford and Pedley (1996). These calcareous strata are commonly overlain by mudstone and fine sandstone of variable thickness, ranging from <1 m to >65 m thick in outcrop. As much as 230 m of clastic Bouse deposits have been interpreted from well logs in Blythe Basin (Metzger et al., 1973). Generally, Bouse deposits are unconformably overlain by coarse alluvial fan deposits or Colorado River sand and gravel deposits, but in some areas fine-grained clastic Bouse deposits are interbedded with sand deposits, apparently supplied by the Colorado River (Buisin, 1990). Tufa was probably deposited (or precipitated) in shallow-water, nearshore environments (Metzger, 1968; Buisin, 1990), and is found through a substantial altitudinal range, especially in the Blythe Basin.

Important considerations for the origin and significance of the Bouse Formation include its distribution, age, and Sr isotopic composition. The maximum elevations of Bouse Formation outcrops are 555 m above sea level (asl) north of Topock Gorge in the Mohave-Cottonwood Basin and 330 m asl to the south in the Havasu Basin and Blythe Basin (Figs. 1 and 2; Spencer et al., 2008a). The age of the Bouse Formation is constrained by two dated volcanic ash beds. In the Mohave-Cottonwood Basin, the Bouse Formation overlies alluvial fan deposits and basin-axis deposits that include the 5.8 Ma (Anders et al., 2009) tuff of Wolverine Creek (House et al., 2008). Near its southernmost extent at Buzzards Peak in the Chocolate Mountains (Fig. 1), Bouse Formation marl contains an ash bed at 306 m elevation that is geochemically correlated with the Lawlor Tuff originating from the Sonoma volcanic field in the northern San Francisco Bay region (Sarna-Wojcicki et al., 2011). Plagioclase from the Lawlor Tuff in central California yielded a 40Ar/39Ar incremental-release isochron age of 4.834 ± 0.022 (2σ) Ma (Sarna-Wojcicki et al., 2011). Strontium isotopic analysis of 55 samples of Bouse carbonates and shells yielded 87Sr/86Sr values between 0.7102 and 0.7114 (Fig. 3; Buisin, 1988; Spencer and Patchett, 1997; Roskowski et al., 2010). Three 87Sr/86Sr analyses of Colorado River water from the lower Colorado River Valley are also in this range (Fig. 3; Goldstein and Jacobsen, 1987; Gross et al., 2001), whereas 87Sr/86Sr of early Pliocene seawater is ~0.7090 (e.g., Farrell et al., 1995).

The nature and stratigraphy of strata in the northern Mohave Valley in the Mohave-Cottonwood Basin is particularly revealing of events associated with Colorado River arrival (Fig. 4; House et al., 2005, 2008). Tilted Miocene fanglomerates are overlain unconformably by alluvial fan deposits derived from bedrock on both sides of the elongate, north-trending valley; distinctive clast types are associated with each side. The Pyramid Hills, located directly north of Bullhead City (Fig. 1) and consisting of distinctive Proterozoic granite, separate the Mohave Valley from the Cottonwood Valley to
the north. These hills were overtopped by water flowing from the north, resulting in catastrophic flood deposits (Pyramid gravel) derived from the Proterozoic granite and deposited south of the Pyramid Hills. These flood deposits are overlain directly by calcareous strata of the Bouse Formation. This sequence is interpreted to represent first-arriving Colorado River water, with catastrophic overflow from the Cottonwood Valley to the Mohave Valley, followed by filling of both valleys by standing lake water to an elevation of ~350 m and deposition of the Bouse Formation (House et al., 2005, 2008). This was followed by lake lowering, presumably due to southward spillover and outflow-channel incision, channel incision through Bouse and related strata, and then aggradation of Colorado River sand and gravel (Bullhead alluvium).

**Lawlor Tuff**

The Amboy calcareous strata contain a volcanic ash bed that is geochemically similar to the ash bed within the Bouse Formation at Buzzards Peak in the Chocolate Mountains (Fig. 5; Buzzards Peak sample JS111305–1 T556–1 is collected at Universal Transverse Mercator geographic coordinate system, zone 11, north- ing 3670812, easting 699088, elevation 306 m), and both have been geochemically correlated with the 4.83 Ma Lawlor Tuff, which originated in the northern San Francisco Bay area (Sarna-Wojcicki et al., 2011). Electron-microprobe analysis of six elements (Si, Al, Fe, Ca, Ti, Mg) in volcanic glass from the Amboy and Buzzards Peak tuffs, and comparisons of the glass compositions with ~5600 samples in the U.S. Geological Survey tephra geochemistry database (http://geomaps.wr.usgs.gov/tephra/index.htm), indicate that these two tuffs are more similar to each other (similarity coefficient = 0.9839) than to any of the other samples in the database (Table 1). The next five tephra samples with the greatest geochemical similarity to the Amboy tephra, all considered to be Lawlor Tuff correlatives, are from widely dispersed sample sites; three are in the San Francisco Bay area (Sonoma volcanic field, Los Medanos Hills, and Livermore Valley in Table 1), one is in the Los Angeles area (Malaga Cove), and one is in the eastern Sierra Nevada (Mono Basin) (Sarna-Wojcicki et al., 2011). Comparison using the same six elements, plus potassium and sodium, is a less reliable correlation indicator because alkalies are more mobile over geologic time, and because laboratory analytical uncertainty has been greater for sodium than for the other major elements. Nevertheless, with the addition of sodium and potassium to the set of elements used in calculating similarity coefficients, the Amboy and Buzzards tephra are more similar to each other than to all but three other Lawlor Tuff samples in the U.S. Geological Survey tephra geochemistry database (Table 2). The strongest correlations are also to a geographically widespread set of tephra samples; five of the top eight matches are from the northeastern San Francisco Bay area. The Huichica tuff, which is also derived from the Sonoma volcanic field and is ~0.1 m.y. younger than the Lawlor Tuff, is chemically similar to the Lawlor Tuff (8 in Table 1, and 30 and 36 in Table 2) but can be distinguished because it contains >~1.0% CaO, whereas the Lawlor Tuff contains <~0.96% CaO (Fig. 14 in Sarna-Wojcicki et al., 2011). Two other candidate tuffs are present much farther north in the central Cascade Ranges; they are Quaternary in age and thus not possible correlatives (26 and 32 in Table 2).

**Yuma Area**

Bouse Formation was mapped by Olmsted (1972) in the U.S. Army Yuma Proving Ground adjacent to the Colorado River north of Yuma (Fig. 1). Reexamination of these strata by two of us (Spencer and Pearthree, with military escort; photos prohibited) identified only quartz-rich sand in broadly lenticular form (1–3 m thick, many tens of meters across) and locally

---

**Figure 2. Graph of elevations of Bouse Formation strata relative to distance north of the Chocolate Mountains. Points below modern river level are based on well logs and were derived from Metzger and Loeltz (1973) and Metzger et al. (1973). Dashed line represents approximate lower bound of Bouse strata. Important new data points are those identified as originating from the northern Mohave Mountains and the two northernmost points in the figure.**
gypsiferous mud that we interpret as overbank deposits. These strata grade upward into tributary gravel deposits. The deposits are lithologically dissimilar to Bouse carbonates and siltstones and are likely related to some phase of more recent Colorado River aggradation. All other possible Bouse Formation strata in the Yuma area are subsurface (Olmsted et al., 1973; McDougall, 2008). Correlation of Bouse strata in the Yuma and Blythe Basins has been supported by similarity of microfossils in the two areas, but correlation has not been documented with published photographs of the relevant microfossils. No calcareous well samples have been located that could be analyzed for $^{87}\text{Sr}/^{86}\text{Sr}$ to evaluate correlation with Bouse carbonates in the Parker-Blythe-Cibola area. We do not dispute that there are fine-grained Miocene to Pliocene marine deposits in the Yuma area, but question whether they should be grouped with Bouse deposits exposed in the lower Colorado River Valley, and consider this issue unresolved.

Frenchman Mountain Area

At Frenchman Mountain east of Las Vegas, marl and algal limestone overlie ~20 m of sandstone that in turn overlies the 5.8 Ma tuff of Wolverine Creek (Castor and Faulds, 2001). These carbonates are thus plausibly equivalent in age to the Bouse Formation (House et al., 2008). Marl from Frenchman Mountain yielded $^{87}\text{Sr}/^{86}\text{Sr}$ values of 0.7107–0.7109 (Fig. 3; Roskowski et al., 2010). These ratios are well within...
the range of Bouse values and are similar to values for modern Colorado River water (Fig. 3). A single analysis of gypsum that underlies, or is laterally equivalent to, the Frenchman Mountain limestone (Duebendorfer, 2003) yielded a slightly lower \(^{87}\text{Sr}/^{86}\text{Sr}\) value that is also well within the range associated with the Bouse Formation (Roskowski et al., 2010).

Hualapai Limestone

Hualapai Limestone is exposed extensively near the mouth of the Grand Canyon in the Grand Wash Trough and farther west in the central Lake Mead area (Beard et al., 2007). In the Grand Wash Trough, Hualapai Limestone was deposited from before 11.0 Ma to after 7.4 Ma and is exposed at elevations of \(-530\) m to \(912\) m asl (Faulds et al., 2001; Wallace et al., 2005).

Hualapai Limestone is exposed in the central Lake Mead area at elevations to \(720\) m asl, and is interbedded with a tuff dated, by \(^{40}\text{Ar}/^{39}\text{Ar}\) incremental-release dating of biotite, as \(5.97 \pm 0.07\) Ma (2\(\sigma\) uncertainty; Spencer et al., 2001).

Figure 4. Schematic cross section of stratigraphic relationships in northern Mohave Valley, showing the Pyramid gravel deposits directly beneath Bouse carbonates. Tephra dates, by geochemical correlation, are from House et al. (2008).

Figure 5. Map of Blythe Basin and western closed basins, showing drainage divides and \(330\) m elevation contour that represents the maximum elevation of known Bouse outcrops. Blythe Basin, defined broadly, is that area that drains into the Colorado River south of Parker Dam and north of the Chocolate Mountains. Also shown are the Buzzards Peak and Amboy tuff sample localities. See Figure 6 for location.
Geosphere, June 2013

449

Similarity Order Lab number Sample number Analysis Date SiO₂ Al₂O₃ Fe₂O₃ MgO MnO CaO TiO₂ Na₂O K₂O Total Sim.Co*

1 5586 JS2706-1 T556-2 (Amboy) 12/4/2007 73.15 14.39 2.24 0.12 0.02 0.89 0.18 4.82 4.19 100.00 1.0000
2 5587 JS111305-1 T556-1 (Buzzards) 12/4/2007 73.62 14.55 2.18 0.12 0.03 0.89 0.19 4.98 3.46 100.02 0.9839
3 4562 EL-102-MS T433-6 (Mono) 1/25/2000 74.43 13.82 2.27 0.12 0.05 0.94 0.17 4.34 3.86 100.00 0.9702

Note: All samples were correlated with the ca. 4.83 Ma Lawlor Tuff except samples 8 and 22 (Sarna-Wojcicki et al., 2011). AVR 43—Average of 43 Lawlor Tuff samples; Hls—Hills; Col.—Collinsville.

The lack of sediment derived from the Colorado River and facies relationships indicate that the Colorado River did not enter the Grand Wash Trough during Hualapai Limestone deposition in that basin (Lucchitta, 1987).

The ⁸⁷Sr/⁸⁶Sr values of Hualapai Limestone are highly variable (0.7114–0.7193), with much scatter and no simple relationship to stratigraphic position within each of three Hualapai subbasins (Lopez Pearce, 2010). The 6 Ma ash bed is approximately in the middle of the Hualapai Limestone in the Temple Bar area of central Lake Mead, which suggests that this section is younger than most or all of the preserved section in Grand Wash Trough. Seven samples from this subbasin yielded ⁸⁷Sr/⁸⁶Sr values of 0.7137–0.7145; the lowest value is from near the top of the succession and above the dated tuff (Fig. 3A; Spencer and Patchett, 1997; Roskowski et al., 2010; Lopez Pearce, 2010). All seven of these ⁸⁷Sr/⁸⁶Sr values are substantially higher than Colorado River water (0.7103–0.7108) and Bouse carbonates (0.7102–0.7114). Highly heterogeneous ⁸⁷Sr/⁸⁶Sr values were inferred by Lopez Pearce (2010) to reflect local sources of spring water rather than a large lake with uniform ⁸⁷Sr/⁸⁶Sr. Such heterogeneity is consistent with facies relationships and detrital zircon data that show no indication of an influx of voluminous Colorado River water and associated sediment (Lopez Pearce et al., 2011). Decreasing ⁸⁷Sr/⁸⁶Sr at the highest stratigraphic levels of the westernmost and youngest Hualapai Limestone exposures might reflect dilution by low-volume input from first-arriving Colorado River water (e.g., Faulds et al., 2001; Roskowski et al., 2010).

INTERPRETATION

Maximum elevations of Bouse Formation outcrops are ~555 m north of Topock Gorge and 330 m to the south (Fig. 2); there are no mapped Pliocene or Quaternary faults that could account for the offset (John, 1987; Howard et al., 1999, 2013). This step-like character of maximum Bouse Formation elevations is consistent with deposition in two lakes that filled previously closed basins inherited from Miocene Basin and Range extension. This was identified previously as a factor supporting a lacustrine interpretation for the Bouse Formation (Spencer et al., 2008a), and is supported by new data points representing the highest Bouse elevations at the southern end of Mohave Valley and fairly far north in Cottonwood Valley (Fig. 2). This step-like elevation character is not consistent with Bouse deposition in an estuary followed by uplift to the north and associated southward tilting, as proposed by Lucchitta (1979), Turak (2000), and Lucchitta et al. (2001).
### TABLE 2. CHEMICAL ANALYSES OF THE AMBOY TEPHRA AND ITS 36 CLOSEST MATCHES FOR ELEMENTS Si, Al, Fe, Mg, Ca, Ti, Na, and K

| Similarity Order | Lab number | Sample number | Analysis Date | SiO₂ | Al₂O₃ | Fe₂O₃ | MgO | MnO | CaO | TiO₂ | Na₂O | K₂O | Total | Sim. Co* |
|------------------|-----------|--------------|--------------|------|-------|-------|-----|-----|-----|------|------|-----|-------|---------|
| 1                | 0000      | 100.00       | 14.39        | 2.24 | 0.12  | 0.02  | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 100.00 | 0.9503  |
| 2                | 2379      | 0000         | 18.14        | 6.48 | 1.00  | 0.07  | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 100.00 | 0.9503  |
| 3                | 4669      | 099.99       | 19.14        | 6.48 | 1.00  | 0.07  | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 100.00 | 0.9503  |
| 4                | 9369      | 000.00       | 11.47        | 6.47 | 1.00  | 0.09  | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 100.00 | 0.9503  |
| 5                | 4959      | 010.00       | 19.14        | 6.48 | 1.00  | 0.07  | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 100.00 | 0.9503  |
| 6                | 6859      | 99.99        | 11.47        | 6.47 | 1.00  | 0.09  | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 100.00 | 0.9503  |

All samples were correlated with the ca. 4.83 Ma Lawlor Tuff except 26, 30, 32, 35, 36 and 37 (Sarna-Wojcicki et al., 2011). AVR 43—Average of 43 Lawlor Tuff samples; Hls—Hills; Col.—Collinsville.

Isotopic analyses of 55 samples of Bouse carbonates and shells and 5 samples of Frenchman Mountain limestone and gypsum yielded $^{87}$Sr/$^{86}$Sr values between 0.7102 and 0.7114, and include the range of values determined for modern lower Colorado River water (Fig. 3). We emphasize that these 60 $^{87}$Sr/$^{86}$Sr analyses, derived from diverse rock types and shells, show no southward decrease in $^{87}$Sr/$^{86}$Sr values (Fig. 3A). The $^{87}$Sr/$^{86}$Sr would be expected to decrease southward in a 350-km-long estuary where radiogenic spring or river water from northern sources mixed with early Pliocene seawater from southern sources, as proposed by Lucchitta et al. (2001) and Crossley et al. (2011). There is no indication of a relationship between $^{87}$Sr/$^{86}$Sr and elevation (Fig. 3B), as would occur in an estuary with a stratified water column in which less saline water from continental sources overlies more saline water from marine sources.

A proposal that stromatolite in Bouse carbonates underwent isotopic equilibration with Colorado River water during post-Bouse time (Lucchitta et al., 2001) is unlikely for two reasons. High-elevation Bouse exposures were never inundated by post-Bouse river water. At Silver Creek in the Black Mountains, for example, thin Bouse marl is underlain and overlain by locally derived alluvial fan deposits (e.g., fig. 6 in Spencer and Patchett, 1997), whereas the maximum aggradation of Colorado River deposits in this area was ~150 m lower (House et al., 2005). Also, Bouse barnacle shells retain delicate laminations with oxygen and carbon isotopic values that vary in a coordinated manner, interpreted as reflecting seasonal variations in carbonate biomineralization (Patchett and Spencer, 2001; Roskowski et al., 2010). Geochemical exchange sufficient to replace stromatolite, as proposed by Lucchitta et al. (2001), would likely have replaced and homogenized carbon and oxygen isotopes as well.

Identification of the 4.83 Ma Lawlor Tuff in the Bouse Formation and in Bristol Basin carbonate sediments indicates subaqueous, carbonate-depositing environments at both localities at the same time. Coeval submergence of the Blythe Basin and Bristol Basin supports the concept of extensive inundation of the lower Colorado River Valley and the southeastern Mojave Desert (Fig. 6). Isotopic similarity of Bouse carbonates to Colorado River water, with no systematic variation in $^{87}$Sr/$^{86}$Sr along the Colorado River Valley, along with maximum elevation distributions, support the concept of flooding resulting from first arrival of Colorado River water. This would have followed the initial development of the modern Colorado River in the region that became the Grand Canyon.
River water and subsequent filling of previously existing lakes in the Bouse-Hualapai lake system assumed modern elevations and no significant faulting-related elevation changes or tectonic tilting. All hypothetical lakes could not have been present simultaneously as evaporation would likely have been sufficient to remove all Colorado River water before spillover of Lake Mohave (Spencer et al., 2008a). Sequential filling and spilling of lakes in the Bouse-Hualapai lake system are inferred to have drained upstream lakes due to incision of outflow channels while filling downstream lakes. The $\delta^{18}$O Sr/$\delta^{86}$Sr sample locations are those of Buisin (1988), Spencer and Patchett (1997), and Roskowski et al. (2010).

Figure 6. Hypothetical maximum extent of the Bouse-Hualapai lake system assuming modern elevations and no significant faulting-related elevation changes or tectonic tilting. All hypothetical lakes could not have been present simultaneously as evaporation would likely have been sufficient to remove all Colorado River water before spillover of Lake Mohave (Spencer et al., 2008a). Sequential filling and spilling of lakes in the Bouse-Hualapai lake system are inferred to have drained upstream lakes due to incision of outflow channels while filling downstream lakes. The $\delta^{18}$O Sr/$\delta^{86}$Sr sample locations are those of Buisin (1988), Spencer and Patchett (1997), and Roskowski et al. (2010).

An estuarine rather than lacustrine origin for the Bouse Formation was favored in Smith's (1970, p. 1417, bracketed information added) paleontological study of the Bouse Formation partly because “The continuous occurrences of [the foram] Amnonia beccarii through thick sections of sediment indicate that conditions favorable to reproduction persisted for a long time.” Such stable environmental conditions were considered unlikely in a lake. However, numerical simulation of arrival of Colorado River water and subsequent filling of previously closed basins along the Colorado River trough indicates that Lake Blythe could have had stable, approximately seawater level salinities for tens of thousands of years (Spencer et al., 2008a). Furthermore, A. beccarii can live and reproduce in both saline lakes (Cann and De Deckker, 1981) and at salinities less than about half that of seawater (Takata et al., 2009).

The presence of the planktic foraminifer Globigerina sp., found primarily in drill samples from below sea level in the axis of Blythe Basin, was interpreted by McDougall (2008) to indicate early marine inundation of the deep axis of Blythe Basin, followed by influx of Colorado River water and development of less saline conditions. Early marine inundation followed by lacustrine inundation to 330 m altitude would require tectonic uplift of an edifice to impound Bouse lake waters after marine inundation and before Colorado River water arrived to fill Blythe Basin. Tectonic construction of such a dam would presumably have resulted from fault-block uplift within the San Andreas transform fault zone, and would have required hundreds of thousands of years to grow to 330 m elevation.

If this had happened, we would expect to find evidence of a lower unit of marine strata overlain by a higher unit of lacustrine strata, with intervening terrestrial deposits or evidence of subaerial exposure, but no such evidence has been identified. Even at the lowest exposures (70 m modern elevation) in Blythe Basin, Bouse carbonates overlying alluvial fan gravels have Colorado River-type $\delta^{18}$O Sr/$\delta^{86}$Sr (Fig. 3B; Roskowski et al., 2010). We conclude that geologic and strontium isotope evidence strongly support an entirely lacustrine origin for the Bouse Formation, and that paleoenvironmental conditions required for Globigerina sp. are less stringent than inferred by McDougall (2008).

Almost all identified Globigerina sp. in the Bouse Formation are from elevations <~100 m (McDougall, 2011). Early Pliocene sea level was inferred by McDougall (2011) to have been 100 m higher than modern sea level, thereby eliminating the necessity for any tectonic uplift following marine inundation of the axis of Blythe Basin. Recent evaluations of sea level during the mid-Pliocene warm period, however, indicate global sea level at 22 ± 10 m higher than modern sea level (Miller et al., 2012b). The modern elevation of the mid-Pliocene highstand shoreline varies over the Earth because Holocene glacial isostatic adjustments following the last glacial maximum are ongoing and isostatic equilibrium has not yet been reached. For example, ongoing isostatic rebound due to deglaciation is associated with inward flow of asthenosphere from surrounding regions, which in turn are subsiding as underlying asthenosphere departs (Mitrovica and Peltier, 1991; Peltier, 1998). Global numerical simulations of this process place the eastern Mojave Desert region in an area where paleosea-shore during the mid-Pliocene warm period would be ~5 m above or below the indicated 22 ± 10 m global sea-level highstand, depending on model parameters for elastic lithospheric thickness and lower mantle viscosity (Raymo et al., 2011). Early Pliocene sea level, as indicated by marine oxygen isotopes, was similar to that during the mid-Pliocene highstand (e.g., Fig. 1 in Raymo et al., 2011). Early Pliocene marine inundation during deposition of Globigerina sp. tests in the Bouse Formation would therefore require ~60–90 m of post-Bouse uplift in the axis of Blythe Basin, not zero, as proposed by McDougall (2011).

The modern Colorado River carries enough salts that seawater-level salinities would be
likely to develop in standing lakes over thousands to tens of thousands of years due to evaporative concentration of salts. Over longer time periods of many tens of thousands to hundreds of thousands of years, evaporite deposits would be expected. The absence of evaporites in the Bouse Formation south of Lake Mead is consistent with geologically brief inundation of fresh to saline lake water, followed by spillover, incision, and development of a through-flowing river. Approximately 30,000 yr of sequential lake filling before spillover of southernmost Lake Blythe was calculated as most likely to lead to marine salinity levels in Lake Blythe that would be hospitable to marine organisms delivered inadvertently by birds (Spencer and Patchett, 1997; Spencer et al., 2008a). The lack of evaporites in Bouse strata, and calculation of time necessary to produce approximately seawater salinities, suggest that initiation of Colorado River flow through the Grand Canyon began only a few tens of thousands of years before 4.83 Ma (Spencer et al., 2008a). Spillover of Lake Blythe to the Salton Trough slightly after 4.83 Ma is suggested by the presence of Lawlor Tuff interbedded with Bouse carbonates at 306 m (modern) elevation, which is almost at the 330 m maximum inferred water level in Blythe Basin.

Calculations of salinity evolution in Bouse lake waters were based on the assumption that initial Colorado River discharge was similar to modern discharge (Spencer et al., 2008a). The presence of voluminous gypsum deposits east of Frenchman Mountain (Duebendorfer, 2003), with 87Sr/86Sr unlike the Hualapai Limestone but of Frenchman Mountain (Duebendorfer, 2003), presence of voluminous gypsum deposits east of Frenchman Mountain (Duebendorfer, 2003), with 87Sr/86Sr unlike the Hualapai Limestone but of Frenchman Mountain implies that initiation of Colorado River flow through the Grand Canyon began only a few tens of thousands of years after 4.83 Ma and that the presence of Lawlor Tuff interbedded with Bouse carbonates at 306 m (modern) elevation, which is almost at the 330 m maximum inferred water level in Blythe Basin.

COLORADO RIVER SAND IN THE SALTON TROUGH

If our chronology for lake spillover and Colorado River integration is correct, then Colorado River sand would not have arrived in the Salton Trough until ca. 4.80 Ma, when all lakes had drained and been replaced by the through-flowing Colorado River without lacustrine impediments to sand transport. Voluminous sand in the upper part of the Mud Hills Member of the Deguynos Formation of the Imperial Group in the Salton Trough has petrographic and detrital zircon characteristics similar to those of modern Colorado River sand (Dorsey et al., 2011; Kimber and Douglass, 2001). The upward transition from marine claystone to sandy marine rhythms of the upper Mud Hills Member has been dated by magnetostratigraphy as ca. 4.9–4.8 Ma (Dorsey et al., 2011; Fig. 7). The marine claystone of the Mud Hills Member overlies the sandy Wind Caves Member of the Latania Formation. The petrographic similarity of Wind Caves Member sands to Colorado River sand led Dorsey et al. (2011) to infer that Wind Caves Member sands were also delivered by the Colorado River. If Wind Caves Member sands were delivered by the Colorado River, and these sands are ca. 5.3–5.2 Ma, as determined by magnetostratigraphy (Dorsey et al., 2011), then the ~0.5 m.y. difference in the age of the Bouse Formation and the age of the Wind Caves Member indicates that some aspect of current interpretations of Colorado River evolution is erroneous.

Possibilities for the origin of this geochronologic discrepancy include the following.

(1) The Lawlor Tuff was incorrectly dated, and is actually ~0.5 m.y. older than reported by Sarna-Wojicki et al. (2011). However, this is unlikely because the 4.83 Ma date is consistent with radiometric dates of closely related, stratigraphically overlying and underlying volcanic units in the San Francisco Bay area (McLaughlin et al., 2004, 2005).

(2) Geochemical correlation of the two tuff beds associated with the Bouse Formation (at Buzzards Peak and Amboy) with the 4.83 Ma Lawlor Tuff is incorrect, and the Buzzards Peak and Amboy tuffs are actually ~0.5 m.y. older than the Lawlor Tuff. This possibility could be addressed with geochronologic studies of the Buzzards and Amboy tuffs and of tuffs beneath the Bouse Formation that would provide new numerical age constraints. We consider mis-correlation unlikely, however, because of the wide distribution and thorough geochemical characterization of the Lawlor Tuff (Sarna-Wojicki et al., 2011; Tables 1 and 2).

(3) Another possibility is that magnetostratigraphic determination of the age of the Wind Caves Member of the Latania Formation is incorrect. The Palm Springs Group overlies the Imperial Group and contains 2 tuff beds dated as 2.60 ± 0.06 Ma and 2.65 ± 0.05 by sensitive high-resolution ion-microprobe U-Pb isotopic analyses of individual zircon grains, with 35 grains analyzed (Dorsey et al., 2011). Two paleomagnetic polarity studies (Opdyke et al., 1977, 2007, 2011) were used to identify the magnetostratigraphy of a stratigraphic section extending stratigraphically downward from the dated tuffs to the Wind Caves Member. The lower part of the quartz-rich Wind Caves Member was identified as located within a reverse-polarity period dated as 5.23–5.89 Ma (paleomagnetic reversal ages from Cande and Kent, 1995), an interval that is separated from the dated tuffs by six reverse-polarity and six normal-polarity periods. Unrecognized fault or fold duplication of two pairs of normal and reverse polarity periods would place the lower Wind Caves Member within a reverse-polarity period dated as 4.62–4.80 Ma, consistent with the indicated arrival of the Colorado River and deposition of the Bouse Formation and the 4.83 Ma Lawlor Tuff. Unrecognized fault or fold duplication of one pair of normal and reverse polarity periods would place the lower Wind Caves Member within a reverse-polarity period dated as 4.89–4.98 Ma, slightly inconsistent with indicated arrival of the Colorado River and deposition of the Bouse Formation and the 4.83 Ma Lawlor Tuff. The Mud Hills Member is identified as containing the Nunivak, Sidufjall, and upper Thvera normal-polarity intervals and intervening reverse-polarity intervals (Fig. 7). Outcrops of the Mud Hills Member are generally poor, bedding attitudes are sparse to absent over large areas on geologic maps (Winker, 1987; Dorsey et al., 2007), and the sampled section crosses a buried inferred fault with hundreds of meters of displacement. At one location on the north side of Fish Creek Wash, the geologic map of Dorsey et al. (2007) shows the base of the Mud Hills Member in a different location than mapped by Winker (1987), and includes a fault that was not mapped by Winker (1987; location A in Fig. 7). However, it is not apparent, even with these discrepancies, that the magnetostratigraphy determined by Dorsey et al. (2007, 2011) is possibly duplicated by folding or faulting.

(4) A fourth hypothesis is that geochronologic studies have all yielded correct results, and that the Colorado River first delivered sands to the Wind Caves Member ca. 5.3 Ma, then the river was blocked by a tectonic dam that impounded Bouse lake waters and resulted in Bouse Formation deposition in Blythe Basin. This was followed, ca. 4.8 Ma, by lake spillover, integration of the modern Colorado River system, and voluminous sand delivery to the Salton Trough that continues to the present. This complex scenario is implausible for several reasons. (1) Construction of a tectonic dam along the early San Andreas transform system would have to have occurred faster than incision through the dam.
by a large river. This appears unlikely as even at high uplift rates the river would have more than sufficient power to erode through a barrier rising across its established course. (2) The Yuma Basin is large yet contains no outcrops of the Bouse Formation carbonates that are so abundant and distinctive north of the Chocolate Mountains. Such outcrops would be expected if the Yuma Basin had been the site of impounded Colorado River water upstream from the San Andreas fault zone. (3) Evaporation from impounded lake water, for ~0.5 m.y., would have produced voluminous evaporites, but none are known. This hypothesis also requires impoundment of Mohave-Cottonwood lake waters and deposition of the Bouse Formation in that basin, followed by overflow and establishment of the through-flowing Colorado River that delivered sand to the Wind Caves Member, in turn followed by tectonic dam construction, impoundment of Blythe Basin lake waters, and deposition of the Bouse Formation in that basin (this would be followed by overflow and integration of the Colorado River in its approximate modern course). In other words, Bouse deposition in the two basins occurred at significantly different times (Mohave-Cottonwood first, Blythe last) that were separated by a period of through-flowing Colorado River water and deposition of the Wind Caves Member.

(5) In a fifth alternative, Kimbrough et al. (2011) proposed that the Wind Caves Member was derived from ancestral Gila River sands, and that the lower Gila River flowed into the ancestral Salton Trough before the Colorado River. This alternative eliminates all geochronologic conflicts and does not require a tectonic dam to impound Blythe Basin lake waters, but may be inconsistent with detrital zircon analyses (D. Kimbrough, 2012, written commun.). In conclusion, we note that the geochronology of river integration is not well understood, and that reconciling conflicting data sets remains a challenge. Interpretations of the lacustrine versus estuarine origin of the Bouse Formation are not, however, affected by this geochronologic discrepancy.

**NUMERICAL SIMULATION**

Identification of limestone and interbedded Lawlor Tuff in Bristol Basin indicates coeval submergence of the Blythe Basin and Bristol Basin (Reynolds et al., 2008; Roskowski et al., 2010; Sarna-Wojcicki et al., 2011). At maximum Bouse Formation elevations and with modern approximate topography, the two areas would have been submerged by a single body of water (Fig. 5). This Bristol Basin extension to Blythe Basin was not included in previous...
Spencer et al.

Numerical simulations that modeled influx of Colorado River water, evaporation, and salt concentration (fig. 6 in Spencer et al., 2008a). Here we present new simulation results that include Bristol Basin as part of the greater Blythe Basin, which would contain a lake at highstand with 20% greater area than the previously modeled lake (Figs. 5 and 6; see Spencer et al., 2008a, for methodology). Constraints on the salinity of Blythe Basin waters are provided by the mix of freshwater, brackish-water, and marine-water fossil organisms in the Bouse Formation. We infer from these fossils that salinity reached a large fraction of seawater salinity (seawater contains 3.5% dissolved salts, equivalent to 35‰).

Weighted average Colorado River salinity (Na+ + Cl−) at Lees Ferry during 23 yr of measurement before the 1963 closure of the Glen Canyon Dam was ~0.115‰ (~0.119‰ including K+) (Irelan, 1971, table 1 therein, total salts/total water). During this time average annual discharge was 15.72 km3 (Irelan, 1971). At the Grand Canyon, for 37 yr before 1963, weighted average Colorado River salinity (Na+ + Cl−) was ~0.146‰ (~0.152‰ including K+) (Irelan, 1971, table 2 therein). During this time average discharge was 14.96 km3 (Irelan, 1971). Assuming similar salinity for the early Pliocene Colorado River, evaporative concentration of salts by a factor of >100 is required to reach seawater salinity levels. Modeled as a single large lake fed by modern Colorado River annual discharge, evaporative concentration of salts by a factor of 100 followed by spillover requires a precise ratio of lake surface area to evaporation rate. Specifically, for a combined Blythe-Bristol lake area of 10,380 km2 and an evaporation rate of 1.441 m/yr, spillover will occur after an ~10-fold increase in salinity due to evaporative concentration, whereas for an evaporation rate of 1.442 m/yr, spillover will not occur, leading eventually to evaporite precipitation (Fig. 8). Only by adjusting evaporation rates at the submillimeter level (i.e., 1 part in 10,000) is it possible to reach a 100-fold increase in salinity followed by spillover. Such a very narrow range of evaporation rates necessary for this salinity increase followed by spillover would have been extremely unlikely, which indicates that other factors must have controlled Lake Blythe salinity.

In previous numerical simulations (Spencer et al., 2008a), Colorado River water abruptly entered a chain of five basins (Hualapai, Las Vegas, Mohave-Cottonwood, Havasu, and Blythe), with sequential filling, evaporative salt concentration, and spillover. Each lake in the sequence initially received more saline water than did its immediately upstream lake. Simulations determined that, as long as water influx was sufficient to overcome evaporation and cause spillover of each lake, salinity was strongly controlled by incision rate into upstream paleodams. These simulations also indicate that approximately seawater-level salinities were possible for Lake Blythe for thousands to tens of thousands of years, without fine tuning of water-influx rates and evaporation rates.

Numerical simulations of lake filling and spilling, with Bristol Basin included as part of Lake Blythe, were conducted for the same range of incision rates as with the previous set of simulations. Because of the larger Lake Blythe surface area (10,380 km2 versus 8663 km2), it was necessary to use a lower evaporation rate (1.26 versus 1.5 m/yr) in order for spillover to occur. This is consistent with evidence for a wetter early Pliocene climate in this region prior to uplift of the coastal ranges in southern California (e.g., Remeika, 2006, 2007). An early spike in salinity determined by previous simulations does not occur because of the lower evaporation rate in the new simulations (Fig. 9). For an incision rate of 0.01 m/yr per 100 m of elevation drop between lakes (e.g., 10 m of elevation drop between 2 lakes would correspond to a modeled incision rate of 0.001 m/yr), Lake Blythe salinities of 10‰–35‰ are maintained for ~30,000 yr, much like a previous simulation (upper solid line in Fig. 9A, heavy line in Fig. 9B).

Quartz-rich sand similar to that transported by the modern Colorado River, as indicated

Figure 8. Calculated evaporative concentration of salts for Blythe Basin without upstream basins. Model water influx rate is 14.96 km3/yr. Note that only by adjusting evaporation rate at the submillimeter level would it be possible to identify an evaporation rate that would lead to salinities of ~30‰ following by spill over.
Age and origin of the Bouse Formation

by detrital-zircon signatures, was deposited in Lake Mohave during deposition of the Bouse Formation in that basin (D. Kimbrough, 2012, written commun.). This sand would not have reached Lake Mohave if any upstream lakes were present and trapped Colorado River bedload. The presence of plateau-derived sand indicates that lakes Las Vegas and Hualapai were short-lived if they existed at all during early filling of Lake Mohave, and so only participated in evaporative concentration of salts before complete filling of Lake Mohave and before any water reached Lake Blythe.

Numerical modeling of a three-lake system rather than a five-lake system, with no evaporation at any time in upstream Lake Las Vegas and Lake Hualapai, can yield salinities of 10%–35% in Lake Blythe for ~25,000 yr (upper solid line in Fig. 10A, heavy line in Fig. 10B). As with previous models, the surface area of all lakes is so great that all Colorado River water would evaporate before spilling over the last lake, but because of outflow-channel incision, the upstream lakes shrink until even the last lake in the system spills and drains. Progradation of a delta into each lake from the inflow channel would also reduce surface area and associated evaporative water loss, but was not simulated. Reduction of upstream-lake surface area due both to outflow-channel incision and delta construction would increase water volume delivered to downstream lakes and promote terminal lake overflow and outflow incision, leading to a through-going river. Reduction of maximum lake volume due to filling by sediment would reduce the time until spillover and result in less saline initial outflow, but also was not modeled.

We conclude, as in a previous analysis (Spencer et al., 2008a), that evaporative concentration of salts in a chain of lakes could lead to salinity conditions in Lake Blythe that were ultimately hospitable for some marine organisms. Large uncertainties are associated with (1) evaporation rate, (2) incision rates over time for each lake-outflow channel, (3) rates of lake-area reduction during delta construction and progradation, (4) rates of sediment filling and corresponding reduction of lake-water volume, (5) early Colorado River annual discharge, (6) early Colorado River water salinity, (7) uncertainty as to the size or even existence of lakes in the Hualapai and Las Vegas basins during early Colorado River discharge to the Mohave-Cottonwood Basin, and (8) changes in basin topography and lake surface area adjacent to the active, early San Andreas fault system, especially for now-closed basin areas west of the lower Colorado River Valley in the Parker-Blythe-Cibola area. Results of simulations indicate the plausibility of salinity increase in Lake Blythe to approximately

Figure 9. Results of numerical simulations of filling, spill over, and outflow incision of Hualapai–Las Vegas–Bouse lake system, showing salinity evolution and including Bristol Basin as part of the area of Lake Blythe inundation (see Spencer et al., 2008a, for methodology; evaporation rate = 1.26 m/yr; Colorado River water influx is 15 km³/yr). (A) Salinity versus time for five-lake system, with incision rate of 0.01 m/yr per 100 m of elevation drop between lakes. Incision rate is a variable that changed continuously with variation in elevation drop between adjacent lakes. Blythe-Basin inundation at the 306 m elevation of the Buzzards Peak tuff locality, as modeled here, occurred at ~26,750 yr (simulation time). (B) Salinity versus time for Blythe Basin using a range of incision rates. Bold line is same as that shown for Lake Blythe in A.
seawater levels, but reveal little about the relative significance of diverse variables in salinity evolution.

Regardless of details of salinity evolution, early Colorado River discharge was sufficient to fill and spill a lake with an area of ~10,000 km². For this to occur, evaporation rates must have been significantly less in early Pliocene time than modern rates of ~2–4 m/yr, and/or river discharge was significantly greater than the current ~15 km³/yr. An alternative, that early Pliocene evaporation rates and Colorado River discharge were similar to modern values, is possible if an areally extensive delta built up to an elevation of >330 m over thousands of square kilometers in the northeastern Blythe Basin, significantly decreasing Lake Blythe surface area and reducing potential lake volume until spillover occurred. River-valley uplands west and southeast of Parker, Arizona, contain river gravels at moderate elevations, but these are not present at the maximum elevations of Bouse Formation strata.

Most measurements of annual evaporation rate in the Mojave-Sonora Desert region are in the 2–3 m/yr range, with rates of ~4 m/yr at Amboy and Death Valley (Table 3; Farnsworth and Thompson, 1982). With modern Colorado River annual discharge of 15 km³/yr, evaporation rates >1.5 m/yr would prevent spillover of the ~10,000 km² paleolake Blythe, while rates of ~1.25 m/yr are conducive to development of seawater-level salinities followed by spillover. Modern evaporation rates are thus much too high to allow filling and spillover of a lake the size of paleolake Blythe. Fossil evidence from the Palm Springs Group in the Fish Creek area indicates that middle Pliocene climate was wetter and supported trees similar to those in modern coastal California (Remeika, 2006, 2007; fossil wood is similar to California bay laurel [Umbellularia californica], California walnut [Juglans californica], Oregon ash [Fraxinus oregona], Buckeye [Aesculus californica], and others).

The strong modern rain-shadow effect due to uplift of the Peninsular and Transverse Ranges had not yet developed. It is also possible that, at 5 Ma, Pacific winter storms delivered more precipitation to the upper Colorado River drainage basin because the Sierra Nevada were lower (Hammond et al., 2012), and that Colorado River discharge was significantly greater than modern discharge. This raises the possibility that the early Grand Canyon was cut by a more voluminous river than the modern Colorado.

CONCLUSION

The estuarine versus lacustrine origin for the Bouse Formation has been a focus of investigation and controversy in part because the two

---

**Figure 10.** Results of numerical simulations of filling, spill over, and outflow incision of a Bouse lake system with only the Mohave Basin, Havasu Basin, and Blythe Basin, showing salinity evolution and including Bristol Basin as part of the area of Lake Blythe inundation (see Spencer et al., 2008a, for methodology; evaporation rate = 1.20 m/yr; Colorado River water influx is 15 km³/yr). (A) Salinity versus time for three-lake system, with incision rate of 0.01 m/yr per 100 m of elevation drop between lakes. Incision rate is a variable that changed continuously with variation in elevation drop between adjacent lakes. (B) Salinity versus time for Blythe Basin using a range of incision rates. Bold line is same as that shown for Lake Blythe in A.
interpretations have much different tectonic implications (cf. Lucchitta, 1979, and Spencer and Patchett, 1997). Fifty-five $^{87}$Sr/$^{86}$Sr analyses of Bouse shells and carbonates, and five from limestone and gypsum in the western Lake Mead area, encompass the range of values that characterize modern Colorado River water, but all are dissimilar to seawater. The absence of a decrease in $^{87}$Sr/$^{86}$Sr with more southern latitude or lower elevation indicates no support for models in which river water and seawater mixed in an estuary and produced gradients in $^{87}$Sr/$^{86}$Sr. The lacustrine interpretation is further supported by the ~225 m step in maximum Bouse elevations at Topock Gorge, which is consistent with Bouse deposition in a chain of lakes that filled from a northern source. Identification of flood deposits from a northern source that directly preceded Bouse Formation deposition, from the north between the Mohave and Cottonwood basins, further indicates a lacustrine origin for the Bouse Formation (House et al., 2005, 2008). Objections to the lacustrine interpretation are based on the presence of fossil marine fauna. We note, however, that there are numerous examples of avian transport of marine invertebrates (e.g., Bachhuber and McClellan, 1977; Patterson, 1987), in some cases over thousands of kilometers (see reviews in Spencer and Patchett, 1997; Spencer et al., 2008a). In a recent example of avian transport of living marine organisms, an ~1 kg leopard shark, alive and with puncture wounds, was dropped onto a southern California golf course 5 km from the ocean, almost certainly by a raptor (CBS News, 2012).

Data presented here support correlation of the tuff at Buzzards Peak with the tuff at Amboy, and support the concept of simultaneous submergence of a large part of the southeastern Mojave Desert region during deposition of Bouse marl and tufa. Geochemical correlation with the Lawlor Tuff (Sarna-Wojcicki et al., 2011) indicates that this inundation had occurred by 4.83 Ma. Inundation of closed basins by Colorado River water without evaporite accumulation (except in the western Lake Mead area) indicates that inundation was geologically brief, and that river influx began shortly before filling of Lake Blythe and deposition of the 4.83 Ma Lawlor Tuff. We conclude that initiation of incision of Grand Canyon by the modern Colorado River began ca. 4.9 Ma, and that the Colorado River reached the early Pliocene Gulf of California by ca. 4.8 Ma. This chronology conflicts with the magnetostratigraphically determined age of the Wind Caves Member of the Imperial Group and the inferred Colorado River origin of Wind Caves sands (Dorsey et al., 2007, 2011). This unresolved issue does not, however, affect the lacustrine interpretation of the Bouse Formation.

Geologic conditions that led to development of saline Lake Blythe were unusual. Specifically, a major river found a new course and entered a semiarid environment with closed basins inherited from previous extensional tectonism. If this river had entered a single closed basin followed by spillover to the sea, salinities near that of seawater without evaporite precipitation would have been highly unlikely. Entry into a chain of closed basins, with delta construction and filling and spilling of each basin so that downstream basins received more saline water than upstream basins, is more likely to lead to marine salinity levels. Numerical simulation of river water entering a chain of basins leads to the interpretation that high lake-water salinities during transient filling and spilling are well within the realm of possibility and depend significantly on the incision rate of outflow channels. Simulations reveal that shrinking upstream lakes deliver progressively less saline water to downstream lakes as the spilling lakes shrink, while evaporative concentration of salts in the terminal lake counterbalances the decreasing salinity of inflow water, potentially leading to stable, high-salinity conditions for thousands of years. We conclude that such a transient, saline, lacustrine environment occurred in Lake Blythe, and that Lake Blythe waters were hospitable to marine organisms inadvertently introduced by birds. The early Gulf of California provided a nearby source of marine fauna, and millions of birds migrating along an early Pliocene Pacific Coast flyway provided potential transport vectors. Lake Blythe thus appears to have been doubly unusual, a large, transient saline lake along a major coastal migratory flyway.

**ACKNOWLEDGMENTS**

We thank Keith Howard, Kristen McDougall, Jerry Smith, Bill Dickinson, Sue Beard, Andy Cohen, David Kimbrough, Becky Dorsey, and Susanne Janecke for discussions and insights over the years that have added to our understanding of the Bouse Formation and Colorado River. We also thank Becky Dorsey for answering several written inquiries with detailed responses concerning Neogene stratigraphy and structure in the Fish Creek area, and Dave Miller and two anonymous reviewers for thoughtful comments that resulted in improvements.

**REFERENCES CITED**

Anders, M.H., Saltzman, J., and Hemming, S.R., 2009, Neogene tephra correlations in eastern Idaho and Wyoming: Implications for Yellowstone hotspot-related volcanism and tectonic activity: Geological Society of America Bulletin, v. 121, p. 837–856, doi: 10.1130/B26300.1.

Bachhuber, F.W., and McClellan, W.A., 1977, Paleocology of marine Foraminifera in the pluvial Estancia Valley, central New Mexico: Quaternary Research, v. 7, p. 254–267, doi:10.1016/0033-5897(77)90004-0.

Bassett, A.M., Kupfer, D.H., and Barstow, F.C., 1959, Core logs from Bristol, Cadiz, and Danby Dry Lakes, San Bernardino County, California: U.S. Geological Survey Bulletin 1045-D, p. 97–138.

Beard, L.S., Anderson, R.E., Block, D.L., Bohannon, R.G., Brady, J.R., Castor, S.B., Duerdendorfer, E.M., Faulds, J.H., Fisher, T.J., Hunt, M.A., and Williams, V.S., 2007, Preliminary geologic map of the Lake Mead 30′ x 60′ Quadrangle, Clark County, Nevada, and Mohave County, Arizona: U.S. Geological Survey Open-File Report 2007-1010, 3 plates, scale 1:100,000, 109 p.

Brown, W.L., and Rosen, M.R., 1995, Was there a Pliocene-Pleistocene fluvial-lacustrine connection between Death Valley and the Colorado River?: Quaternary Research, v. 43, p. 286–296, doi:10.1006/qres.1995.1035.

Buising, A.V., 1988, Depositional and tectonic evolution of the northern proto-Gulf of California and Lower Colorado River, as documented in the Mio-Pliocene Bouse Formation and bracketing units, southeastern California and western Arizona [Ph.D. thesis]: Santa Barbara, University of California, 196 p.

Buising, A.V., 1990, The Bouse Formation and bracketing units, southeastern California and western Arizona: Implications for the evolution of the proto-Gulf of California and the lower Colorado River: Journal of Geophysical Research, v. 95, p. 6093–6095, doi:10.1029/94JB09098.

Cann, J.H., and De Deckker, P., 1981, Fossil Quaternary and living foraminifera from athalassic (non-marine) saline lakes, southern Australia: Journal of Paleontology, v. 55, p. 660–670.
Age and origin of the Bouse Formation

Peltier, W.R., 1998, Postglacial variations in the level of the sea: Implications for climate dynamics and solid-Earth geophysics: Reviews of Geophysics, v. 36, p. 603–689, doi:10.1029/98RG02638.

Poulson, S.R., and John, B.E., 2006, Ancestral woodlands of the Colorado River and the Salton Sea: Proceedings of the 2008 Desert Symposium: California State University, Desert Studies Consortium and LSA Associates, Inc., p. 62–67.

Remeika, P.A., Dettman, D.L., Faulds, J.E., and Reynolds, A.C., 2010, A Late Miocene–Early Pliocene chain of lakes fed by the Colorado River: Evidence from Sr, C, and O isotopes of the Bouse Formation and related units between Grand Canyon and the Gulf of California: Geological Society of America Bulletin, v. 122, p. 1625–1636, doi:10.1130/B30186.1.

Raymo, M.E., Mitrovica, J.X., O’Leary, M.J., DeConto, R.M., and Hearty, P.J., 2011, Departures from eustasy and sea-level records: Nature Geoscience, v. 4, p. 328–332, doi:10.1038/ngeo1118.

Remeika, P., 2006, Ancestral woodlands of the Colorado River delta plain, in Jefferson, G.T., and Lindsay, L., eds., Fossil treasures of the Anza-Borrego Desert: San Diego, California, Sunbelt Publications, Inc., p. 75–87.

Remeika, P., 2007, Pliocene angiosperm hardwoods and recycled Cretaceous palynoflora of the ancestral Colorado River, Anza-Borrego Desert State Park, California: A review, in Reynolds, R.E., ed., Wild, scenic, and rapid: a trip down the Colorado River trough: Abstracts of the 2007 Desert Symposium: California State University, Desert Studies Consortium and LSA Associates, Inc., p. 76–82.

Reynolds, R.E., Miller, D.M., and Bright, J., 2008, Possible Bouse Formation in the Bristol Lake basin, California, in Reynolds, R.E., ed., Trough to trough: The Colorado River and the Salton Sea: Proceedings of the 2008 Desert Symposium: California State University, Desert Studies Consortium and LSA Associates, Inc., p. 62–67.

Spencer, J.E., and Pearthree, P.A., 2001, 40Ar/39Ar geochronology of the Hualapai Limekiln Member of the Bouse Formation and implications for the age of the lower Colorado River, in Young, R.A., and Spamer, E.E., eds., The Colorado River: Origin and evolution: Grand Canyon Association Monograph 12, p. 89–91.

Spencer, J.E., Pearthree, P.A., and House, P.K., 2008a, An evaluation of the evolution of the latest Miocene to earliest Pliocene Bouse lake system in the lower Colorado River Valley, southwestern USA, in Reheis, M.C., et al., eds., Late Cenozoic drainage history of the southwestern Great Basin and lower Colorado River region: Geologic and biologic perspectives: Geological Society of America Special Paper 439, p. 375–390; doi:10.1130/2008.2439(17).

Spencer, J.E., Smith, G.R., and Dowling, T.E., 2008b, Middle to late Cenozoic geology, hydrography, and fish evolution in the American Southwest, in Reheis, M.C., et al., eds., Late Cenozoic drainage history of the southwestern Great Basin and lower Colorado River region: Geologic and biotic perspectives: Geological Society of America Special Paper 439, p. 279–299; doi:10.1130/2008.2439(12).

Spencer, J.E., Peters, L., McIntosh, W.C., and Patchett, P.J., 2001, 40Ar/39Ar geochronology of the Hualapai Limekiln Member of the Bouse Formation and implications for the age of the lower Colorado River, in Young, R.A., and Spamer, E.E., eds., The Colorado River: Origin and evolution: Grand Canyon Association Monograph 12, p. 89–91.

Spencer, J.E., Pearthree, P.A., and House, P.K., 2008a, An evaluation of the evolution of the latest Miocene to earliest Pliocene Bouse lake system in the lower Colorado River Valley, southwestern USA, in Reheis, M.C., et al., eds., Late Cenozoic drainage history of the southwestern Great Basin and lower Colorado River region: Geologic and biologic perspectives: Geological Society of America Special Paper 439, p. 375–390; doi:10.1130/2008.2439(17).

Spencer, J.E., Smith, G.R., and Dowling, T.E., 2008b, Middle to late Cenozoic geology, hydrography, and fish evolution in the American Southwest, in Reheis, M.C., et al., eds., Late Cenozoic drainage history of the southwestern Great Basin and lower Colorado River region: Geologic and biotic perspectives: Geological Society of America Special Paper 439, p. 279–299; doi:10.1130/2008.2439(12).

Spencer, J.E., Peters, L., McIntosh, W.C., and Patchett, P.J., 2001, 40Ar/39Ar geochronology of the Hualapai Limekiln Member of the Bouse Formation and implications for the age of the lower Colorado River, in Young, R.A., and Spamer, E.E., eds., The Colorado River: Origin and evolution: Grand Canyon Association Monograph 12, p. 89–91.

Takata, H., Dettman, D.L., Seto, K., Kurata, K., Hiratsuka, J., and Khim, B.K., 2009, Novel habitat preference of Ammonia beccarii form 1 in a macrobenthos community on hard substrates in the Ohashi River, southwest Japan: Journal of Foraminiferal Research, v. 39, p. 87–96, doi:10.2113/gsjfr.39.2.87.

Todd, T.N., 1976, Pliocene occurrence of the recent atherinid fish colopichthys regis in Arizona: Journal of Paleontology, v. 50, p. 462–466.

Turak, J., 2000, Re-evaluation of the Miocene/Pliocene depositional history of the Bouse Formation, Colorado River trough, southern Basin and Range (CA, NV, and AZ): M.S. thesis, Laramie, University of Wyoming, 96 p.

Wallace, M.A., Faulds, J.E., and Brady, R.J., 2005, Geologic map of the Meadowview North Quadrangle, Mohave County, Arizona and Clark County, Nevada: Nevada Bureau of Mines and Geology Map M-154, scale 1:24,000, 22 p.

Winker, C.D., 1987, Neogene stratigraphy of the Fish Creek–Vallecito section, southern California: Implications for early history of the northern Gulf of California and Colorado Delta [Ph.D. thesis]: Tucson, University of Arizona, 494 p.