Paleogeomorphology and evolution of the early Colorado River inferred from relationships in Mohave and Cottonwood valleys, Arizona, California, and Nevada

Philip A. Pearthree[1],* and P. Kyle House[2]
[1]*Arizona Geological Survey, 416 W. Congress Street, Tucson, Arizona 85701, USA*
[2]*U.S. Geological Survey, 2255 N. Gemini Drive, Flagstaff, Arizona 86001, USA*

ABSTRACT

Geologic investigations of late Miocene–early Pliocene deposits in Mohave and Cottonwood valleys provide important insights into the early evolution of the lower Colorado River system. In the latest Miocene these valleys were separate depocenters; the floor of Cottonwood Valley was ~200 m higher than the floor of Mohave Valley. When Colorado River water arrived from the north after 5.6 Ma, a shallow lake in Cottonwood Valley spilled into Mohave Valley, and the river then filled both valleys to ~560 m above sea level (asl) and overtopped the bedrock divide at the southern end of Mohave Valley. Sediment-starved water spilling to the south gradually eroded the outlet as siliciclastic Bouse deposits filled the lake upstream. When sediment accumulation reached the elevation of the lowering outlet, continued erosion of the outlet resulted in recycling of stored lacustrine sediment into downstream basins; depth of erosion of the outlet and upstream basins was limited by the water levels in downstream basins. The water level in the southern Bouse basin was ~300 m asl (modern elevation) at 4.8 Ma. It must have drained and been eroded to a level <150 m asl soon after that to allow for deep erosion of bedrock divides and basins upstream, leading to removal of large volumes of Bouse sediment prior to massive early Pliocene Colorado River aggradation. Abrupt lowering of regional base level due to spilling of a southern Bouse lake to the Gulf of California could have driven observed upstream river incision without uplift. Rapid uplift of the entire region immediately after 4.8 Ma would have been required to drive upstream incision if the southern Bouse was an estuary.

*phil.pearthree@azgs.az.gov

INTRODUCTION

Deposits of the latest Miocene or early Pliocene Bouse Formation and slightly younger, unequivocal deposits of a through-flowing Colorado River provide critical evidence regarding the inception and early evolution of the Colorado River. Both sets of deposits are exposed throughout the lower Colorado River (LCR) valley from the Chocolate Mountains of southeastern California northward to Cottonwood Valley in Arizona and Nevada (Fig. 1). The fine-grained sediments of the Bouse Formation were deposited on a landscape of bedrock hillslopes, alluvial fans, and axial valley deposits that was broadly similar to the one we see today, except that there is no evidence of a through-flowing fluvial system linking basins from north to south prior to Bouse deposition. The interval of Bouse deposition was succeeded by accumulation of a thick sequence of primarily quartz-rich sand and far-traveled rounded gravel deposits, the Bullhead alluvium (House et al., 2005, 2008b; Howard et al., 2015). These deposits were clearly transported and emplaced by the Colorado River. These two sets of deposits record a dramatic change in the geomorphology of this area, and they are intimately involved in the initial development of the LCR.

In this paper we focus on the latest Miocene and early Pliocene deposits and paleogeomorphology of Mohave (MV) and Cottonwood Valleys (CV), before, during, and after the arrival of Colorado River water and sediment. Detailed geologic mapping and reconnaissance investigations in the past 15 yr (Howard et al., 1999, 2013; Faulds et al., 2004; House et al., 2004, 2005, 2008a, 2008b; Pearthree and House, 2005; Spencer et al., 2007; Pearthree, 2007; House and Faulds, 2009; Malmon et al., 2009; Pearthree et al., 2009; Howard et al., 2013) have greatly enhanced our understanding of the distribution of Bouse deposits and their relationships to the underlying paleolandscape and to the obvious Colorado River deposits that immediately succeeded them. The primary purposes of this paper are to (1) draw upon this recent work to reconstruct the general characteristics of the landscape and depositional systems that existed in these valleys immediately prior to Bouse deposition; (2) describe the character and distribution of Bouse deposits in these valleys, and how their characteristics vary with landscape position; (3) describe the Bullhead alluvium and summarize the stratigraphic and geomorphic relationships between Bouse and Bullhead deposits; (4) consider the implications of this evidence for changing regional base level through a scenario of lake and river evolution; and (5) consider the competing hypotheses explaining Bouse deposition and LCR development in the context of the current constraints on the magnitude and timing of base-level changes in the LCR valley.

We use elevations relative to modern sea level for the vertical positions of various outcrops, paleovalleys, and paleo–water bodies in the modern landscape. This is not intended to exclude the possibility that local deformation or regional uplift has changed absolute elevations of various outcrops and landscape features after Bouse and Bullhead deposition. By using this convention, we make no assumptions about whether elevations of deposits and landscape features throughout the region have changed relative to sea level or to each other since 5 Ma.

PREVIOUS WORK

The Bouse Formation was first thoroughly described and defined by seminal geohydrology studies conducted in the 1960s (Metzger, 1968; Metzger et al., 1973; Metzger and Loeltz, 1973). The studies correlated Bouse outcrops within and between basins based on similar physical characteristics, including basal carbonate
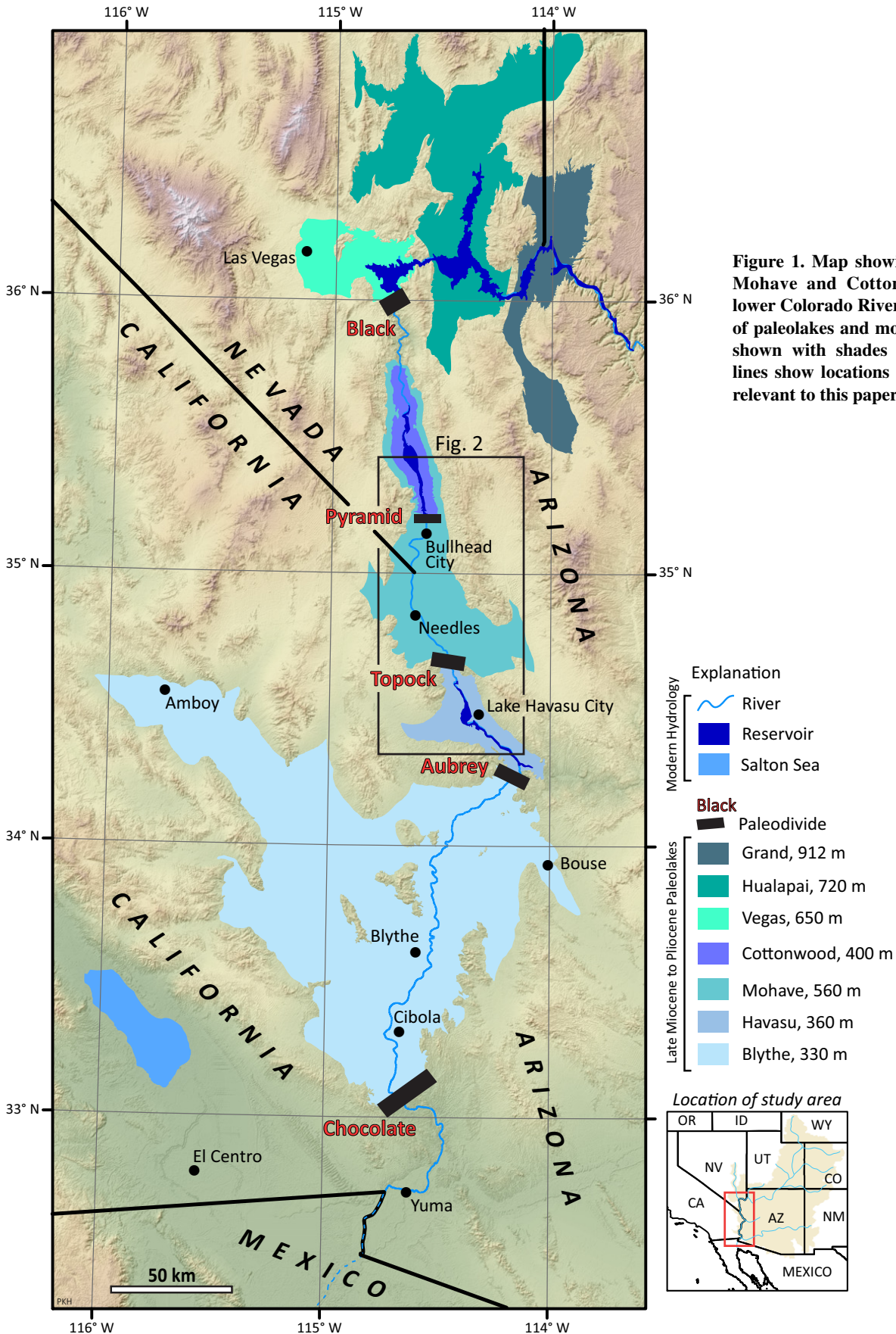
Figure 1. Map showing regional setting of Mohave and Cottonwood Valleys in the lower Colorado River Valley. Inferred areas of paleolakes and modern water bodies are shown with shades of blue. Heavy black lines show locations of inferred paleodams relevant to this paper.

(micritic limestone, marl, carbonate-cemented sandstone), tufa deposits, and much thicker clay, silt, and sand deposits of the interbedded unit. Deposits interpreted to be Bouse Formation range in elevation from ~200 m below sea level to 330 m above sea level (asl) in the Parker-Blythe-Cibola (PBC) area (Fig. 1) (Metzger et al., 1973; Spencer et al., 2013), from ~100 to 370 m asl in Chemehuevi Valley (Metzger and Loeltz, 1973; our data), and from ~50 to 560 m asl in the Mohave-Cottonwood area (Metzger and Loeltz, 1973; our data). The constraints on the age of Bouse deposits were quite broad; it was considered to be late Miocene to Pliocene in age (Metzger, 1968), ca. 5.5 Ma (Lucchitta, 1979), or between 8 and 3 Ma (Buising, 1990).

Paleontological and sedimentologic investigations led many researchers to conclude that all of the Bouse Formation was deposited in an estuary. The presence of fossil fish, mollusks, and foraminifera (forams) interpreted to be marine organisms in the PBC area (e.g., Smith, 1970; McDougall, 2008) led to the conclusion that the Bouse was an estuarine deposit related to initial opening of the Gulf of California (Metzger, 1968; Metzger et al., 1973; Metzger and Loeltz, 1973). Depositional environments recorded by the Bouse Formation were further described and interpreted by Buising (1990) in the PBC area and by Turak (2000) at selected localities from Cibola to CV; they interpreted sedimentary features to be estuarine and concluded that all of the Bouse Formation represents a marine incursion into a subsiding trough related to the opening of the Gulf of California. Lucchitta (1972, 1979) and Lucchitta et al. (2001) argued that the Bouse Formation was deposited in a deep, subsiding, sinuous trough that extended along the LCR valley to the mouth of the Grand Canyon; they hypothesized that this subsidence induced headward erosion into the Grand Canyon region, which resulted in capture or diversion of the upper Colorado River into the Bouse embayment. Based on the interpretation that all of the Bouse Formation was deposited in an estuary, and thus the highest Bouse deposits record a paleo–sea-level datum, Lucchitta (1979) inferred substantial regional uplift increasing to the north in the LCR region, and interpreted the thick siliciclastic Bouse facies as a Colorado River delta complex that gradually filled the marine embayment. Regional uplift began shortly after the subsidence that facilitated Bouse deposition. If the uppermost Bouse outcrops record paleo–sea level in the latest Miocene to early Pliocene, then the lowest Bouse deposits in the subsurface imply that the base of Bouse deposition was 500 m (MV) to 530 m (Blythe area) below sea level at that time.

Spencer and Patchett (1997) and Meek and Douglas (2001) revived the idea originally suggested by Blackwelder (1934) that the Bouse Formation records a series of lakes sequentially filled by a downstream-developing LCR spilling through formerly closed basins, ultimately linking to the upper end of the Gulf of California. Strontium isotope ratios determined for Bouse carbonate deposits throughout their latitudinal and elevation ranges are similar to one another and to modern Colorado River values, but are not consistent with late Miocene marine water (Spencer and Patchett, 1997; Poulson and John, 2003; Roskowski et al., 2010). As additional Bouse outcrops have been discovered and documented in more detail, it is apparent that their maximum elevations rise to the north in a step-wise fashion mediated by bedrock divides, a pattern that is consistent with a north to south progressive lake spilling (Spencer et al., 2008, 2013). Our previous work described a fluvial-boulder-conglomerate unit (the Pyramid gravel) at the base of the Bouse deposits in northern MV as evidence for north to south spilling from CV to MV, which is consistent with entry of river water from the north (House et al., 2005, 2008b). In the lacustrine Bouse hypothesis, regional uplift or warping is not required to explain the modern elevations of the Bouse Formation because they are relicts of a stair-stepping cascade of lake systems.

Hybrid models in which some part of the Bouse Formation was deposited in an estuary, and some was deposited in lakes, have been proposed recently. Based primarily on paleo-ecological interpretations, Miller et al. (2014) concluded that the Bouse Formation in the PBC area, and spreading far across the eastern Mojave Desert, was deposited in an estuary that existed at 4.8 Ma. The surface of this postulated estuary is now at least 300 m asl, so this interpretation requires substantial regional uplift after 4.8 Ma. McDougall and Miranda Martínez (2014) interpreted forams recovered from Bouse deposits in the PBC area to indicate marine conditions to at least 110 m asl. Some of these forams may date to the late Miocene, suggesting the possibility of an early incursion of seawater into the LCR valley that may have been followed by estuarine or lacustrine deposition recorded by the higher portions of the Bouse Formation. Crossey et al. (2015) present a new analysis of isotopic signatures in the Bouse Formation, and conclude that Sr ratios from the northern Bouse basins are dominated by Colorado River water with some local sources, but that isotopic values in the PBC basin could be produced by mixing of Colorado River water and seawater.

The major post-Bouse Colorado River aggradation represented by the Bullhead alluvium

was also recognized (Unit B of Metzger et al., 1973; Metzger and Loeltz, 1973). Based on outcrops and well cuttings, Metzger et al. (1973) and Metzger and Loeltz (1973) described a suite of primarily quartz-rich sand and rounded, lithologically diverse river gravel in erosional contact with Bouse deposits; they interpreted these deposits as the earliest evidence for the existence of the through-flowing LCR. These deposits are found along the LCR from the mouth of the Grand Canyon to the modern delta; they are much coarser than Bouse deposits, and have sedimentological characteristics consistent with subaerial deposition in a major river system (Metzger and Loeltz, 1973; House et al., 2005, 2008b; Howard et al., 2015). Thus, Bullhead deposits represent the first definitive evidence of the existence of the continuous LCR ending at the Gulf of California. Detrital zircon age analyses of sand samples from Bullhead deposits are very similar to samples of modern Colorado River deposits, implying that the early LCR drained a similar watershed (Kimbrough et al., 2011, 2015). Bullhead deposits record a period of major aggradation by the Colorado River, as they are found from below the modern floodplain to as much as 250 m above the river. They are much coarser than younger Colorado River deposits such as those of the late Pleistocene Chemehuevi Formation (Malmon et al., 2011). The thickness and coarseness of the Bullhead alluvium indicate that it represents an early pulse of anomalously high sediment supply in the Colorado River watershed (House et al., 2008b; Howard et al., 2015).

AGE CONSTRAINTS

Investigations of the past 15 years have tightened constraints on the age of Bouse and Bullhead deposition in CV and MV, as well as the LCR as a whole. In CV, we found an outcrop of the 5.5–5.6 Ma Conant Creek Tuff (or possibly the closely related Wolverine Creek tephra) sourced from the Heise volcanic field in Idaho (Morgan and McIntosh, 2005) in fine-grained basin-axis deposits as deep as ~60 m beneath the base of Bouse deposits (House et al., 2008b). Outcrops of the same tephra have been found in alluvial fan deposits ~10 m below Bouse deposits on the Black Mountains piedmont in northern MV (House et al., 2008b). Thus, Bouse deposition in these valleys clearly postdates 5.6 Ma, but the amount of time that passed between tephra and Bouse deposition is uncertain. The 4.1 ± 0.5 Ma tuff of Artists Drive[1] (Knott and Sarna-Wojcicki, 2001; Knott et al.,

---

[1]Previously called "lower Nomlaki tephra" in House et al. (2005, 2008b).

2008) provides evidence for the age of maximum Colorado River aggradation. This tephra has been found at numerous places in central and northern MV and in CV (House et al., 2008b; Pearthree et al., 2009; E. Wan, U.S. Geological Survey, 2010, written commun.). In three localities in MV, the tuff of Artists Drive is in tributary fan deposits overlain by Bullhead alluvium between 360 and 390 m asl, just below the maximum level of river aggradation. We found the 3.3 Ma Nomlaki tephra (Sarna-Wojcicki et al., 1991) in younger tributary gravel deposits that truncate the highest levels of Bullhead alluvium and were graded to a river level that was at least 50 m below the maximum level of Bullhead aggradation (House et al., 2008b). Thus, Bouse deposition, Bouse incision, Bullhead aggradation, and initial post-Bullhead incision in MV and CV all occurred between 5.5 and 3.5 Ma. In the area south of Parker, the ca. 4.8 Ma Lawlor Tuff has been identified in Bouse carbonate deposits at ~300 m asl in 2 widely separated localities (Spencer et al., 2013; Miller et al., 2014; Sarna-Wojcicki et al., 2011). Presumably this tephra was deposited on or washed into the Bouse water body near the time when the maximum water level (~330 m asl) was attained in the PBC area. Paleomagnetic stratigraphy and paleontology have been used to estimate an age of 5.3 Ma for the first arrival of distinctive Colorado River sand in the Salton Trough (Dorsey et al., 2007). It is not clear how this apparent age discrepancy can be reconciled (Spencer et al., 2013). At Sandy Point, just below the mouth of the Grand Canyon, a 4.4 Ma basalt flow is intercalated in a thick sequence of coarse Colorado River deposits (Faulds et al., 2001). Thus, major Colorado River aggradation we correlate with the Bullhead alluvium (Howard et al., 2015) was ongoing at that time.

PRE-BOUSE LANDSCAPE

Mapping and investigations conducted in the past 15 years have greatly increased our knowledge of the extent and character of Bouse deposition, and provide much more information about the landscape upon which the Bouse Formation was deposited. Prior to these recent studies, little was known about the landscape in CV when Bouse deposition began, as only one associated outcrop was reported in this valley (Metzger and Loeltz, 1973, p. 10). Although parts of CV have not yet been explored for Bouse deposits, known Bouse outcrops extend intermittently for 17 km on the east side of the valley, and more limited outcrops have been found on the west side of the valley (Fig. 2). Metzger and Loeltz (1973) identified thick siliciclastic Bouse out-

crops in the central and southern parts of MV, and some thin piedmont carbonate, tufa, and clastic deposits scattered around the valley margins. Recent investigations have identified many more carbonate and tufa outcrops and a thick siliciclastic Bouse section in Secret Pass Canyon. In addition, we found critically important Bouse outcrops in the basin axis in northern MV (House et al., 2005, 2008b). Most of the newly discovered Bouse outcrops in both valleys are relatively thin and are found on middle and upper piedmonts where underlying deposits are exposed, or mantling bedrock paleotopography. Although the record is still quite fragmentary and will always be limited because most of the Bouse Formation in these valleys has been removed by erosion, we have a much better data set for reconstructing the landscape that existed when the Bouse Formation was deposited.

Basal Bouse deposits were draped over a landscape consisting of alluvial fans, bedrock hillslopes, eroded slopes on older fanglomerate units, and axial valley drainages and playas. Basal outcrops overlie alluvial fan deposits in the majority of exposures. It is common for the alluvial fan surfaces to be very well preserved with no evidence of significant erosion of the surface associated with Bouse deposition, but locally lenses and beds of rounded locally derived gravel and sand likely record nearshore wave activity. Where Bouse water inundated bedrock outcrops or older eroded fanglomerate deposits, carbonate and tufa deposits drape over gently to steeply sloping colluvium-mantled paleohillslopes and exposed bedrock faces. Exposures of basal Bouse deposits in the basin axes are much less common, but basal carbonate overlies fine gravel, sand, silt, and clay in these locations.

In CV, the base of the Bouse deposits can be observed or closely constrained for nearly all outcrops because incision by the Colorado River and tributaries has eroded the valley well below the base of Bouse deposition. Bouse deposits have been completely removed by erosion in the axis of central CV, but they are exposed on indurated alluvial fan deposits in middle and upper piedmont areas on both flanks of the valley at elevations ranging from 340 to 550 m asl. Alluvial fans on the pre-Bouse piedmonts sloped toward the valley axis at angles that are similar to or slightly greater than the slopes of modern piedmont washes, 3°–4° on the eastern piedmont and 2.5°–3° on the western piedmont (see Fig. 3). The elevation of the basin depocenter in the central CV at the time of Bouse deposition is constrained to between 280 m and 340 m asl, based on the highest preserved outcrop of the underlying fine-grained basin-fill deposits informally named the Lost Cabin beds

(House et al., 2005) and the lowest Bouse outcrop on distal alluvial fan deposits.

Farther south in CV, Bouse deposits are widely exposed in deeply incised valleys east of the Colorado River. In this area, the vast majority of Bouse outcrops overlie moderately indurated alluvial fan deposits. Sub-Bouse alluvial fan surfaces slope 2.5°–4° to the west, but decrease to <2° in exposures nearer the paleovalley axis.

The westernmost Bouse outcrops are on a gently north sloping surface above fine gravel, sand, silt, and clay strata, including some weakly to moderately developed buried soils (Lost Cabin beds; House et al., 2005). Miocene alluvial fan deposits from the Newberry Mountains on the west side of CV crop out east of the Colorado River beneath the Lost Cabin beds. These deposits are remnants of alluvial fans that extended from major drainages from the northern Newberry Mountains. Their position on the east side of the modern river indicates a valley axis location farther to the east prior to Bouse deposition (Fig. 2). Fan deposits derived from the Newberry Mountains grade upsection into the lower, gravelly part of the Lost Cabin beds, which include gently dipping strata with clasts from the Newberry Mountains and the Black Mountains. The Lost Cabin beds fine upward and to the north; we interpret these beds as evidence for an aggrading pre-Bouse axial drainage that was fed by alluvial fans draining from each side of the valley farther south. Elevations of the base of the Bouse over Lost Cabin beds in this area range from 365 to 350 m asl, decreasing to the north. All of this is consistent with alluvial fans graded to a basin axis fluvial system that sloped <1° north toward a depocenter in central CV.

In MV, contacts between Bouse deposits and underlying units are widely exposed on upper piedmonts, less commonly on middle and lower piedmonts, and rarely in the basin axis (Fig. 3). In northern MV, basal Bouse deposits are exposed in the basin axis and on both eastern and western piedmonts. Several Bouse outcrops exposed in the middle and upper western piedmont indicate that the paleoslope of 3°–4° was similar to that of the modern piedmont. On the east side of the valley, the highest observed Bouse outcrops are on alluvial fan deposits that dip 2°–2.5°, generally to the west. In Secret Pass Canyon a few kilometers north, the base of the Bouse Formation is well exposed over alluvial fan deposits that slope ~3°–4° to the west. Because the paleofan slopes are greater than the modern wash, the base of the Bouse disappears beneath the modern wash bed at ~400 m asl.

In the axis of northern MV, the boulder-rich Pyramid gravel (House et al., 2005, 2008b),
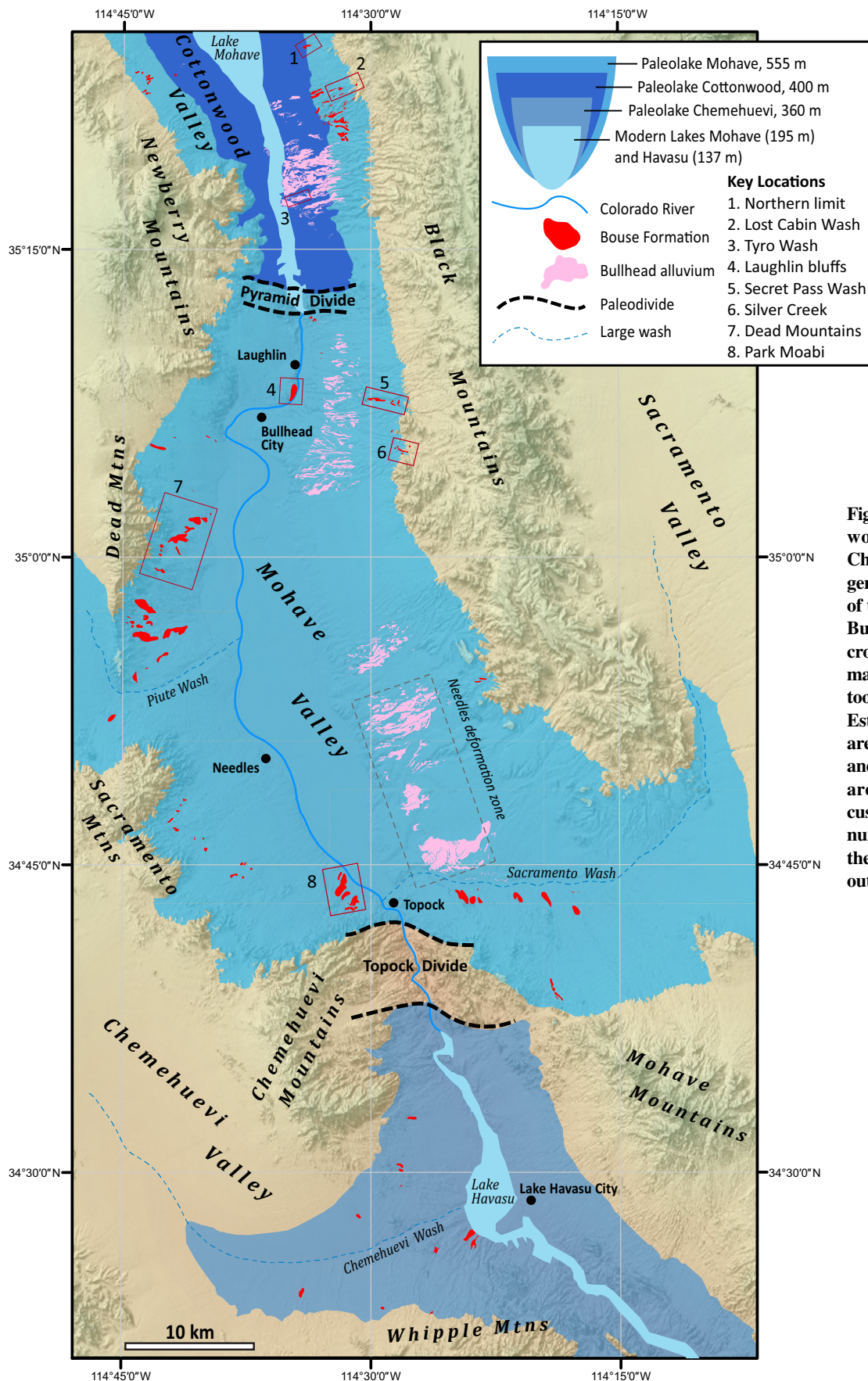
Figure 2. Map of southern Cottonwood, Mohave, and northern Chemehuevi Valleys showing the general distribution of outcrops of the Bouse Formation (red) and Bullhead alluvium (pink). Outcrops are slightly generalized, and many isolated Bouse outcrops are too small to depict at this scale. Estimated extents of paleolakes are depicted with shades of blue, and rough extents of paleodivides are shown. Key locations discussed in the text are identified by number. The approximate area of the Needles deformation zone is outlined with a dashed box.
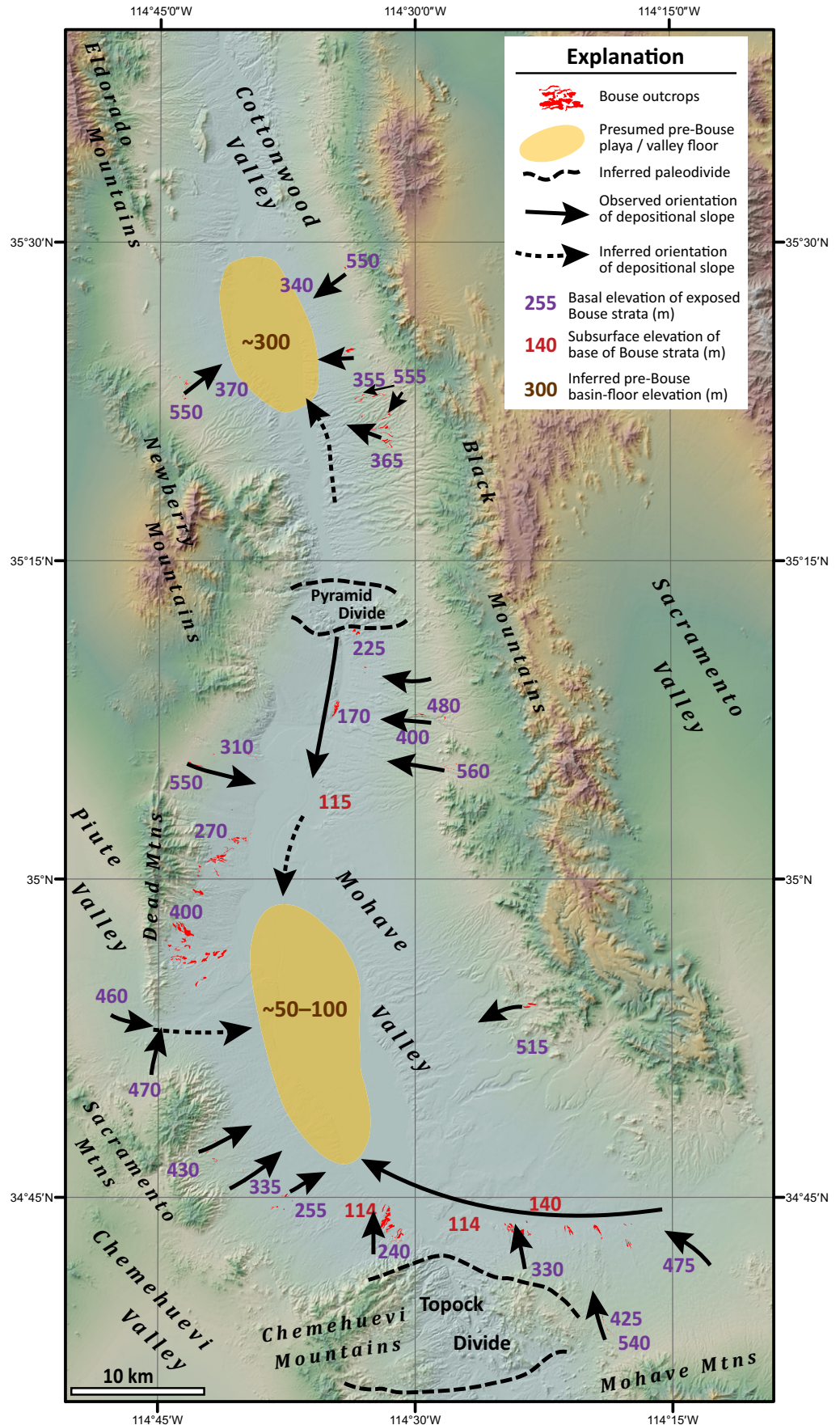
Figure 3. Map illustrating the paleogeography and drainage systems of Cottonwood and Mohave Valleys prior to the arrival of Colorado River water. Purple numbers are selected elevations above sea level in meters of basal Bouse outcrops; red numbers indicate the base of the Bouse in the subsurface inferred from well logs. Tan blobs illustrate the approximate extents of the inferred playas in central Cottonwood Valley and central and southern Mohave Valley. Arrows indicate slopes inferred for immediately pre-Bouse alluvial fans and axial drainages.

which we propose as a member of the Bouse Formation, is on an erosion surface cut on local alluvial fan deposits and relatively small, south-directed axial valley channels. The valley axis in this area dipped ~1° south from ~190 to 160 m asl; ~7 km farther south, the base of the Bouse is ~115 m asl (interpreted from a well log by Metzger and Loeltz, 1973), consistent with a flattening paleovalley axis slope of ~0.5° to the south. Farther south the depth of the base of the Bouse is not well constrained, but it evidently continues to slope very gently to the south into central and southern MV (Fig. 4).

The thickest and most extensive Bouse deposits in these valleys are in central and southern MV, but their bases are exposed in only a few localities around the basin margins and the depth of the Bouse in the valley axis is poorly constrained. Basal Bouse deposits are exposed primarily in upper piedmont areas along the Sacramento Mountains on the west side of the valley, the north flanks of the Chemehuevi and Mohave Mountains on the south side of the valley, and locally along the Black Mountains on the east flank of the valley. In addition, Bouse outcrops extend into Piute Valley to the west and Sacramento Valley to the east, indicating that the valleys drained into MV before Bouse deposition began. On the piedmonts, paleofan surfaces clearly dipped toward the valley axis, with slopes ranging from 1.5° to 4.5°. The steepest fan slopes existed on the northern piedmont of the Chemehuevi Mountains (3°–4.5°), steepening toward the mountains. The long piedmonts east of the Sacramento Mountains and north of the Mohave Mountains sloped much less steeply (1.5°–2°), and the entrances of Piute and Sacramento Valleys sloped ~1°–2° toward MV (Figs. 2 and 3). The east front of the Dead Mountains is exceptional because the only exposures of the base of the Bouse are on bedrock slopes, and thick siliciclastic Bouse deposits bank up against these slopes (Fig. 5). Thus, the contact between the topographic mountain front and piedmont alluvial fans was below the depth of modern exposure in this part of the valley.

The base of the Bouse in the axis of central and southern MV can be roughly inferred from well logs, although there is substantial uncertainty in this data source. Available driller's logs are of variable quality, and diagnostic basal Bouse carbonate is not identified in most logs. In addition, because the lowest part of the valley was certainly receiving fine-grained siliciclastic sediment prior to Bouse deposition, it is not possible to confidently and unequivocally identify the base of Bouse deposits from existing data. This part of the valley axis may have subsided since Bouse deposition. The Needles deforma-tion zone extends for ~20 km on the eastern piedmont of central and southern MV. It has accommodated at least 20 m of down-to-the-west Quaternary displacement (K.A. Howard, *in* House et al., 2005; Pearthree et al., 2009). We do not know the lateral extent of subsidence associated with this displacement, but the axis of central and southern MV may have been low-ered, and thus accumulated a thicker sequence of sediment supplied by the Colorado River in the Pliocene–Quaternary. Although there is substantial uncertainty in our estimate of the pre-Bouse elevation of the basin depocenter at 5 Ma, it was almost certainly below 100 m asl in central or southern MV, and may have been below 50 m asl if post-Bouse deformation has not been an important factor. The basin axis sloped toward this low from the north, and allu-vial fan surfaces sloped toward it from the east, west, and south.

A bedrock topographic divide (the Pyra-mid paleodivide) separated CV and MV, and another divide (the Topock paleodivide) separated MV from Chemehuevi Valley to the south. The Pyramid paleodivide was in the area of a low, east-west–trending set of bed-rock hills informally named the Pyramid hills (Fig. 1). Projecting the axial valley slope in CV to the south, we estimate that the elevation of the divide between the valleys must have been above 380 m asl. Projecting the slope on the erosional base of the Bouse deposits (Pyramid gravel member) northward to the area of Pyramid paleodivide suggests an elevation of ~300 m asl, but this probably reflects erosion of the divide related to spillover from CV rather than initial divide height, or perhaps there was a substantial increase in slope approaching the divide from the south.

Mohave Valley and Chemehuevi Valley are separated by the Topock paleodivide, which is composed of a range of bedrock hills extending between the Mohave Mountains on the southeast and the Chemehuevi Mountains on the northwest (Fig. 1). The Colorado River has incised deeply through this area and much of the paleodivide is highly eroded (Fig. 3). Based on the distribu-tion of the highest Bouse deposits in MV and CV and our inference that these deposits record a deep lake, the low point in this paleodivide would have been ~560 m asl. Bouse outcrops to 540 m asl present immediately northeast of the inferred paleodivide were deposited on a north-sloping piedmont that drained to southern MV; this constrains the location of the paleodivide on the east (Fig. 3). The highest Bouse outcrops yet discovered in Chemehuevi Valley are dra-matically lower, 360–370 m asl. There are no Bouse outcrops in the eroded bedrock hills of the Topock paleodivide, and thus no basis for directly estimating the height of the paleodivide to 560 m asl, or 300 m asl as inferred by Turak (2000) and utilized by McDougall and Miranda Martínez (2014).

CHARACTER AND DISTRIBUTION OF THE BOUSE FORMATION

We group the deposits of the Bouse Forma-tion in MV and CV into three general facies associations: limited initial spillover deposits; a widespread basal or perimeter carbonate unit and associated coarse clastic shoreline and near-shore deposits; and a fluviolacustrine basin-fill unit primarily composed of interbedded mud and sand deposited in association with delta for-mation in the lake. Initial spillover deposits, the Pyramid gravel (House et al., 2005), have been identified only in the axis of northernmost MV (Fig. 6). This very poorly sorted fluvial con-glomerate consists of clasts of megacrystic Pre-cambrian granite derived from the Pyramid hills to the north ranging in size to large boulders, and lesser amounts of Tertiary granite reworked from local alluvial fan deposits. In bluffs imme-diately south of the Casino Strip in Laughlin, Nevada, the 25–30-m-thick Pyramid gravel deposits are on a south-sloping erosion surface cut primarily on alluvial fan deposits dominated by clasts derived from the Newberry Mountains to the west. We interpret the Pyramid gravel as having been emplaced by one or more sub-stantial southward-directed flooding events that eroded the bedrock hills between the two val-leys; this flooding was associated with the ini-tial spillover of water from a fairly shallow lake in CV into the substantially lower MV (House et al., 2005, 2008b). Pyramid gravel deposits are conformably overlain by a thin section of the basal Bouse carbonate unit, which we inter-pret as indicating inundation of the spillover area by lake water filling MV and eventually both valleys.

Deposits of the second association are the most common and widespread Bouse deposits. They consist primarily of carbonate deposits, including micritic white to tan, thin-bedded carbonate (marl, limestone), calcareous local sandstone, and tufa. We have found concen-trations of rounded, locally derived, pebble to cobble gravel in association with the basal car-bonate in a few areas and interbedded locally derived gravel and sand layers are exposed in some outcrops. Basal carbonate deposits were predominantly deposited on alluvial fan sur-faces, but locally form conspicuous drapes and encrustations over bedrock topography (Fig. 7). Nearly every outcrop of the base of the Bouse section consists of carbonate deposits. In many outcrops, only relatively thin (<0.5–2 m) car-
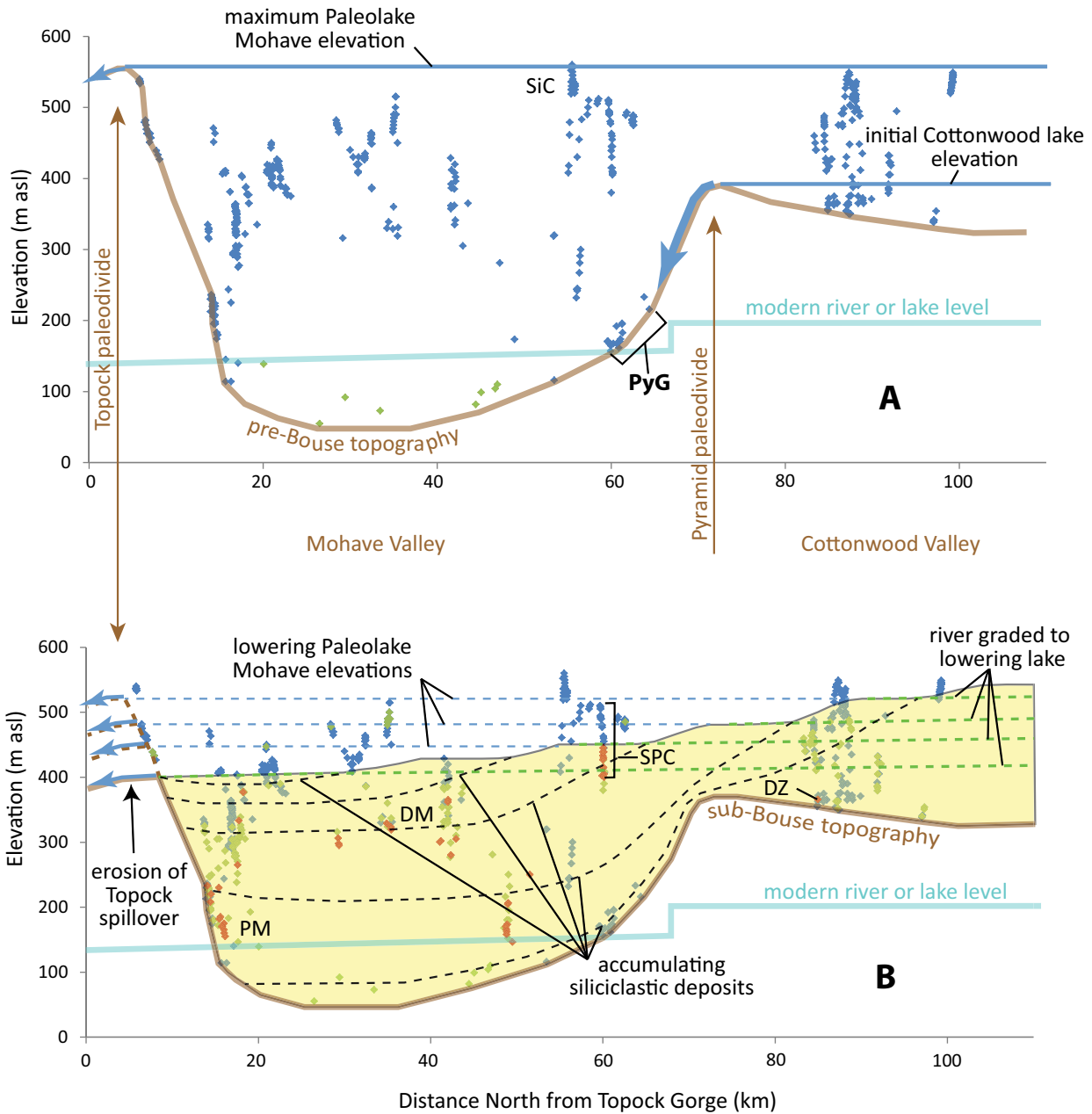
Figure 4. Projections of Bouse deposit localities from the east and west sides of the valleys onto a north-south plane. Bouse data points below the modern river or lake level are from wells logs. (A) Basal and/or perimeter points (blue diamonds) represent Bouse deposits directly over alluvial deposits or bedrock on the valley sides. Fine siliciclastic Bouse deposits are shown only in the subsurface to define the pre-Bouse topography. The Pyramid gravel (PyG) in northern Mohave Valley records the initial spillover of a relatively small lake in Cottonwood Valley. This was followed by lake level rise to a maximum of 555–560 m above sea level (asl) recorded at Silver Creek (SiC), then spilling over the Topock paleodivide. (B) Fine silt and clay deposits (pale green diamonds) are common and have been found as high as to 500 m asl. These deposits would have been suspended sediment and could have been widely distributed in the lake and draped over the lake bottom. Quartz-rich sand deposits (orange diamonds) generally are turbidite deposits in deep water, for example in the Park Moabi (PM) and Dead Mountain piedmont (DM) areas. The detrital zircon analysis of a quartz-rich sand bed near the base of a Bouse outcrop in Cottonwood Valley (DZ) showed similarity to Colorado River sand (Kimbrough et al., 2015). The highest sand deposits grade upward into local gravel deposits at Secret Pass Canyon (SPC) at 430–440 m asl. Dashed gray lines depict hypothetical delta tops graded to decreasing lake levels (dashed blue lines) due to spillover erosion. The valleys filled with Colorado River siliciclastic delta deposits as the lake level lowered (tan color); dashed gray dashed lines represent the advancing delta front with time. Dashed green lines depict river gradients graded to these lake levels, and would have been cut into older delta deposits in the north.
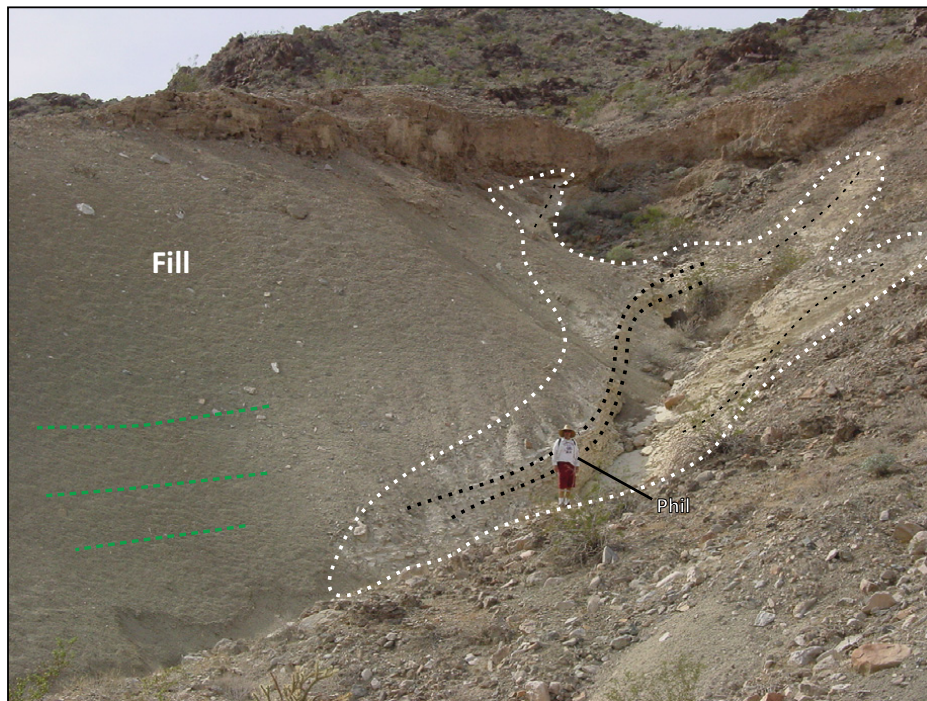
Figure 5. Thin Bouse basal carbonate drape on a steep paleohillslope at the northern end of the Dead Mountain front is indicated by white dashed line. Black dashed lines indicate general slope of bedding in the basal carbonate deposits. Much thicker greenish-gray siliciclastic Bouse deposits banked up against the carbonate drape are highlighted by green lines. Bouose deposits are overlain by carbonate-cemented colluvium.

bonate deposits are preserved on top of indurated fanglomerate beds. The upper ~1 m of the underlying fanglomerate is commonly oxidized and locally appears wave worked and/or sorted. In many outcrops, indurated gray fanglomerate overlies Bouse carbonate on an obvious erosional unconformity. In some outcrops, carbonate deposits are overlain by much thicker fine-grained siliciclastic deposits of a basin-fill association (discussed in the following). Exposures of Bouse carbonate deposits range from 340 m to 550 m asl in CV. In MV, carbonate exposures range from 180 m at the base of the Chemehuevi Mountain piedmont to 560 m in Silver Creek, and they almost certainly exist in the subsurface in southern and central MV. In the highest Bouse outcrops in the exceptionally well preserved Silver Creek section, carbonate deposits are interbedded with local calcareous sand and gravel deposits (Fig. 7F), and there are increasing amounts of coarse clastic deposits upsection and to the east. This sequence clearly records the interaction of lacustrine and tributary fan sedimentation at the lake margin as it was approaching its highest level and greatest areal extent. In this area, in situ tufa deposits that formed in shallow water are found from 520 to 552 m asl (Fig. 7D), limestone grading upward into calcareous sandstone and locally

derived gravel is exposed from 535 to 555 m asl (Figs. 7E, 7F), and a thin calcareous sandstone bed between fanglomerate deposits is exposed ~555–560 m asl. Outcrops of the perimeter association have been found above 530 m asl on 5 other piedmonts around CV and MV, but none of these are as well preserved or well exposed. We infer that imperfect preservation accounts for the fact that they are not quite as high as the Silver Creek section.

The third association consists of much thicker deposits of clay, silt, and quartz-rich sand deposits that overlie the basal and perimeter deposits in many locations (the interbedded unit of Metzger et al., 1973). These deposits represent lacustrine and fluviolacustrine basin fill, the sediment accumulating via deltaic progradation into these valleys (Turak, 2000, also interpreted these as delta and delta-front deposits, as did Buising, 1990, for very similar deposits in the Parker area). Relatively thick sections of clay, silt, and sand (Fig. 8) are most extensive on the Dead Mountains piedmont, but are also found on piedmonts below the Sacramento, Chemehuevi, and Mohave Mountains. In each of these areas, fine siliciclastic outcrops are found to the lowest level of exposures, and similar deposits have been reported from well logs to <55 m asl beneath central MV. Clay and silt deposits as thick as several meters have

been found as high as 500 m asl in CV, but no quartz-rich sand deposits have been found above 440 m asl in either valley.

Preserved siliciclastic Bouse deposits are uncommon in CV, but we have found poorly exposed outcrops as thick as 10 m. These deposits are almost entirely clay and silt, and likely represent suspended load sediments that were dispersed widely in the lake. We found a 0.5-m-thick layer of pink, quartz-rich sand at the base of the Bouse section in one locality south of Lost Cabin Wash (Fig. 8A). A detrital zircon analysis of this sand bed yielded an age spectrum very similar to that of modern Colorado River sand (Kimbrough et al., 2015), indicating that this sand was delivered by the Colorado River. In the western and southwestern portions of MV, the cumulative exposed section of siliciclastic deposits ranges from ~150 to 400 m asl. Quartz-rich, fining-upward sand beds interbedded with clay and silt that are found in some of the lowest exposed Bouse sections near the modern axis of likely are turbidite deposits (Turak, 2000; Reynolds et al., 2007). Similar fining-upward sand beds are common at higher stratigraphic levels on the Dead Mountain piedmont. Quartz-rich sandy deposits are increasingly common higher in this section, suggesting more proximal delta deposition.

The thick siliciclastic section exposed in Secret Pass Canyon may record the maximum level of fluviolacustrine sedimentation in northern MV. In Secret Pass Canyon, an ~40-m-thick Bouse section above a thin basal carbonate layer consists of clay, silt, quartz-rich sand, and locally derived gravel. Deposits immediately above the basal carbonate are primarily clay and silt, with sand and locally derived gravel increasingly common higher in the section. In the highest part of this section, sand and silt beds clearly interfinger with beds of locally derived gravel (Fig. 9A). Farther west and slightly lower, the contact between Bouse deposits and overlying fanglomerate is erosional (Fig. 9B). Given the elevation of the top of this sequence (435–440 m asl) and its gradual transition upward into local fan deposits, we infer that the well-preserved eastern end of this section records the approximate level of maximum siliclastic lacustrine deposition in that part of the lake (see Fig. 4B). We interpret the erosional contact farther west as indicating fan progradation onto eroding Bouse deposits as local base level was lowered due to initial post-Bouse incision in the valley axis.

Even though thick sequences of the lake-sediment-filling association are fairly common in MV, they represent a small fraction of the former valley fill, and thus provide a fragmentary record of Bouse deposition. For example,
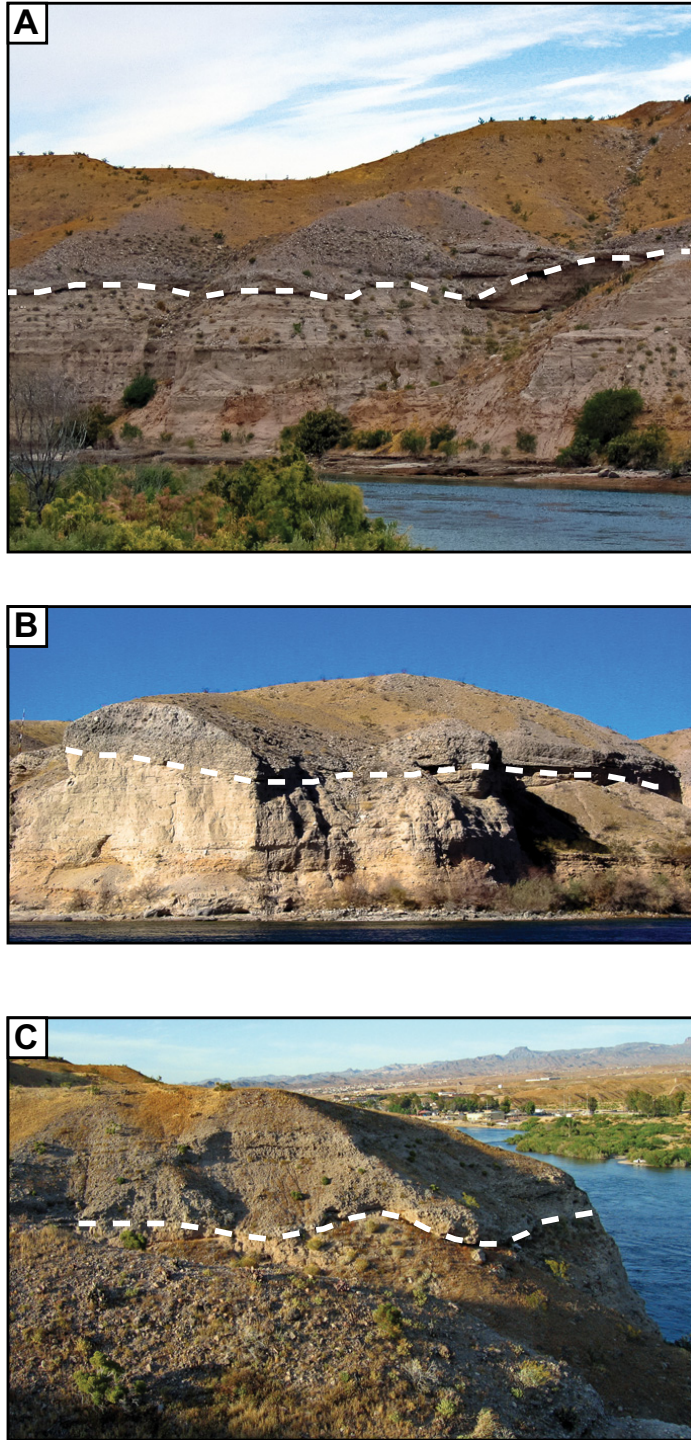
Figure 6. The Pyramid gravel exposed in the Laughlin bluffs just south of Laughlin, Nevada, records the initial spilling of paleolake Cottonwood into Mohave valley. In each photo, the dashed white lines highlight the undulating erosional contact between the Pyramid gravel above, dominated by dark Precambrian granite clasts derived from the Pyramid hills to the north, and local late Miocene fanglomerate dominated by light colored Oligocene–Miocene granite clasts.

the developing LCR was almost certainly supplying some gravel to MV and CV, but we have not yet found any rounded, far-traveled river gravel in the basin-fill association. In the PBC basin farther south, Metzger et al. (1973) reported small amounts of fine rounded gravel in some beds in their interbedded unit in the subsurface, and Buising (1990) reported rounded river pebbles from outcrops of the Bouse Formation south of Parker. We presume that fine river gravel likely would have been included in the deltaic deposits in the northern valleys as well, but that deep post-Bouse erosion has removed all of these deposits in the valley axes.

DEVELOPMENT AND DEMISE OF PALEOLAKE MOHAVE

The distribution of the perimeter carbonate association and the basin-fill fluviolacustrine association provide important clues to the evolution of paleolake Mohave. The basin-fill unit is enclosed on its base and lateral margins by the basin perimeter association, which extends higher in the landscape to approximately the maximum extent of the lake inundation. The highest preserved deposits of the basin perimeter association indicate that the elevation of maximum lake filling was as high as 560 m asl. The top of the highest thick siliciclastic section is ~440 m asl in Secret Pass Canyon, where quartz-rich sand and silt beds grade upward into locally derived gravel deposits. We interpret the basin-perimeter association as evidence for an influx of carbonate-rich Colorado River water. The carbonate deposits likely accumulated primarily in shallow water, but may also have accumulated in deep water where siliciclastic deposition was minimal (Turak, 2000). The carbonate deposits line basin floors and lateral margins, recording the progressive deepening and areal expansion of paleolake Mohave and the upslope migration of shorelines. The lake continued to deepen and expand until a paleodivide in the Topock area at ~555–560 m asl was overtopped; after that time, erosion of the outlet lowered lake level. During this time of lake filling and initial spillover, siliciclastic sediment may have been stored in upstream lakes along the LCR, or was deposited in a growing delta in northern CV. The thick basin-filling association records the progradation of a delta wedge, the finer deposits representing primarily prodelta, deep-water deposition, and sandy deposits recording both turbidite deposition in deep water and more proximal delta deposition.

The demise of paleolake Mohave did not require that siliciclastic sedimentation reached the level of maximum lake filling, but rather that the sedimentation level eventually reached
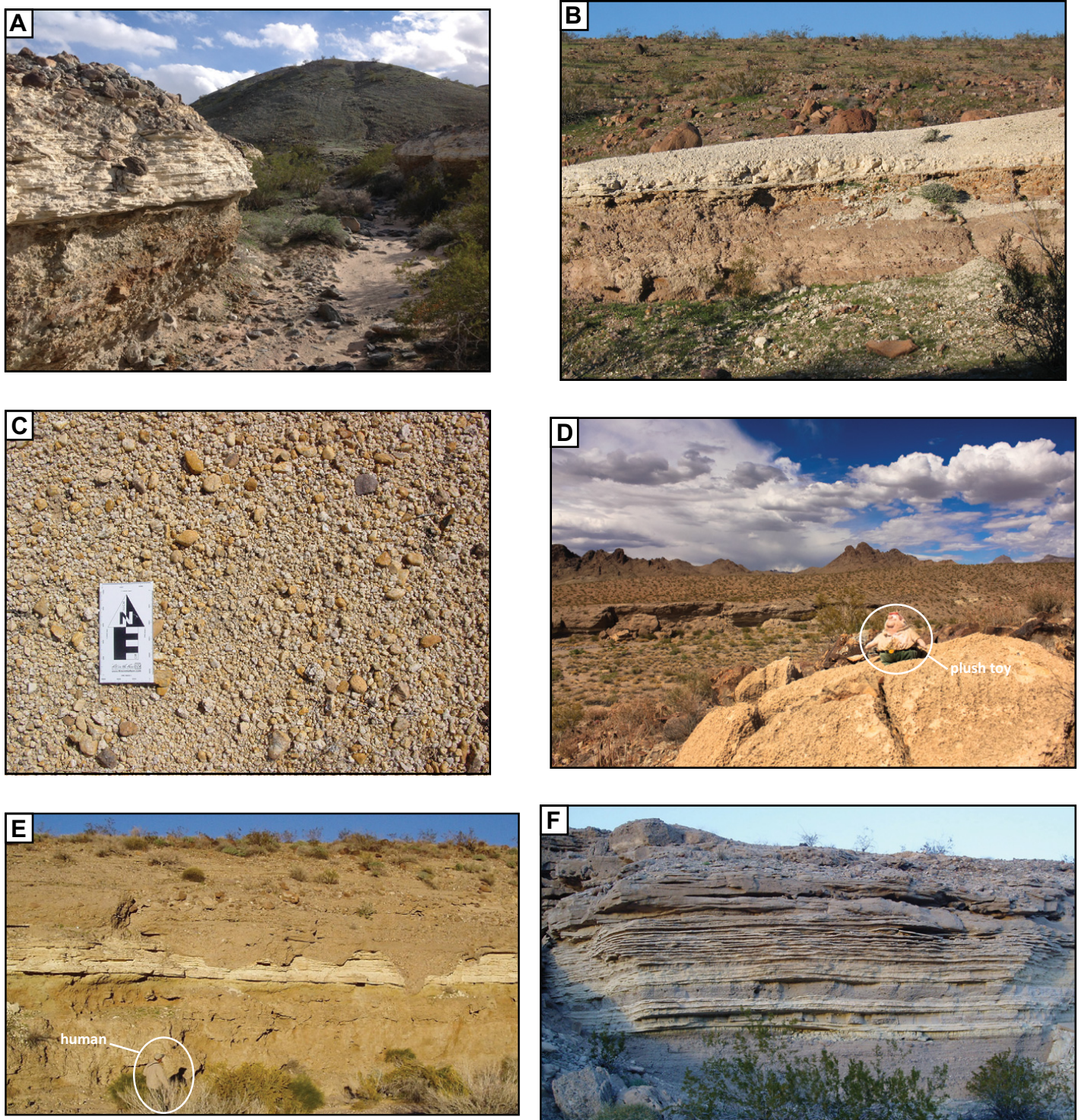
Figure 7. Examples of the basal and perimeter Bouse carbonate deposits. (A) 1-m-thick basal carbonate over oxidized fanglomerate at ~180 m above sea level (asl), Park Moabi area. (B) 0.5–1-m-thick basal carbonate over oxidized fanglomerate layers at ~400 m asl, north of Lost Cabin Wash in Cottonwood Valley. (C) Oxidized rounded locally derived gravel form a surface lag above basal Bouse carbonate at ~490 m asl, northern Mohave Valley. (D) Massive tufa deposit on bedrock at 552 m asl, Silver Creek (~10-cm plush toy for scale). (E) Exposure of basal carbonate over oxidized fanglomerate at 530 m asl, Silver Creek (note person for scale); overlying indurated fanglomerate is on erosion surface cut on Bouse deposits, including small channels cut into and through the Bouse deposits. (F) Farther east at 550 m asl, white Bouse limestone beds are on local fanglomerate and are interbedded with tan local sand and gravel fanglomerate, with more gravel higher in section (section is 8–10 m thick) These deposits clearly record interplay between local tributary deposition, quiet-water lacustrine deposition, and probably wave reworking of the clastic deposits.

Figure 8. Examples of typical delta and prodelta facies of the Bouse Formation. (A) Quartz-rich pink sand bed in finer grained clay and silt beds at 365 m above sea level (asl) in Cottonwood Valley is highlighted by red dashed lines. Sand bed is on orange oxidized silt and clay beds, and is overlain by several meters of greenish clay beds (note hat for scale). (B) Exposure of thick section of interbedded mud and sand on the upper piedmont of the Dead Mountains, central Mohave Valley (light colored beds higher in section). The left base of this exposure is 315 m asl, the exposed section is ~20 m thick, and Bouse deposits are erosionally truncated by younger fan gravel. (C) Detail of part sequence containing repeated of couplets of very fine sand and silt with massive claystone (pick is ~30 cm long). (D) Fining-upward tan sand beds (some prominent beds highlighted with dashed red lines) in greenish-gray clay and silt deposits near Park Moabi, southern Mohave Valley. The base of the exposure is ~170 m asl. The sand beds likely record prodelta turbidites deposited in deep water, with finer grained deposits representing the gradual settling of suspended load (after Turak, 2000).
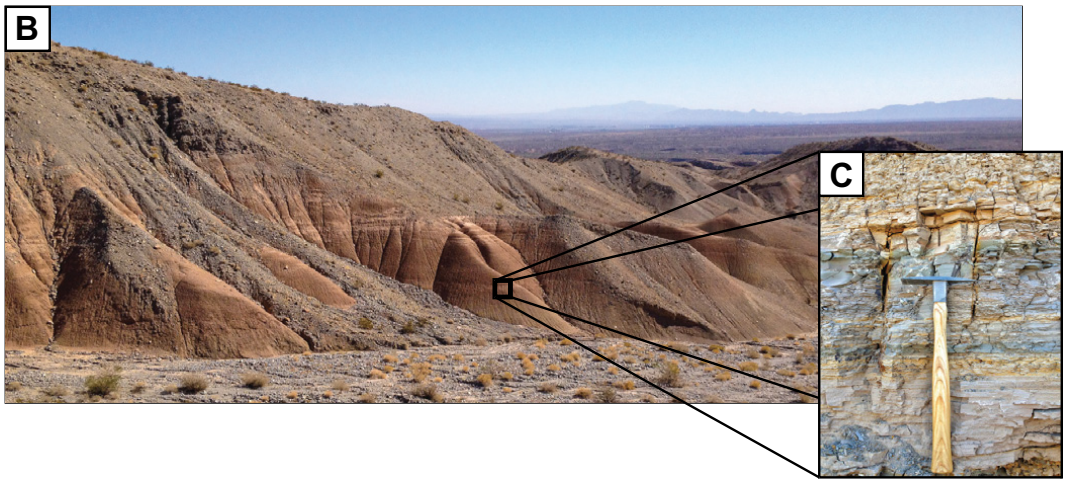
Figure 9. Upper fluviodeltaic Bouse deposits in Secret Pass Canyon. (A) In the eastern, highest part of the exposure, Bouse sands are interbedded with locally derived gravel layers and lenses, and grade upward into fanglomerate. The base of this exposure is ~430 m above sea level (asl). (B) Farther west and slightly lower, the contact between Bouse deposits and overlying fanglomerate is clearly erosional.
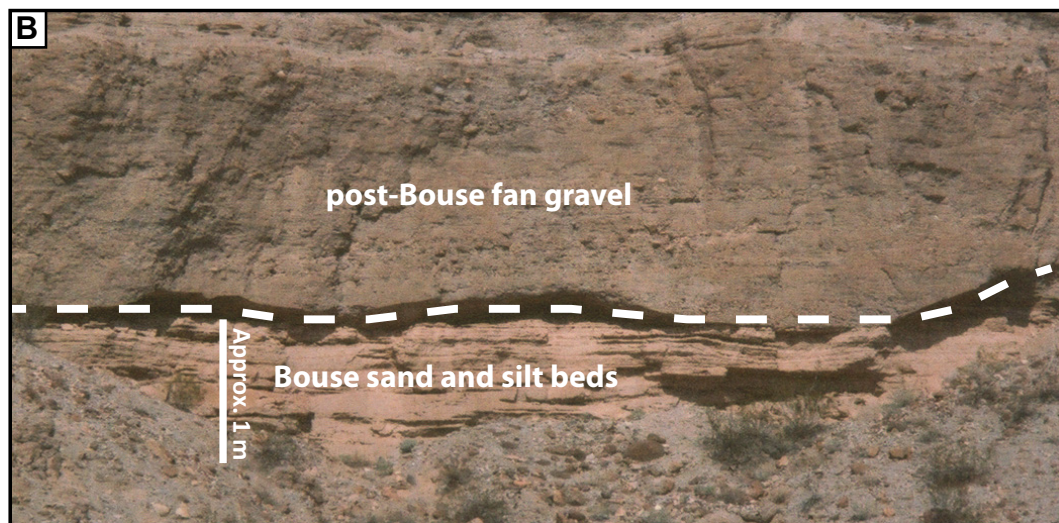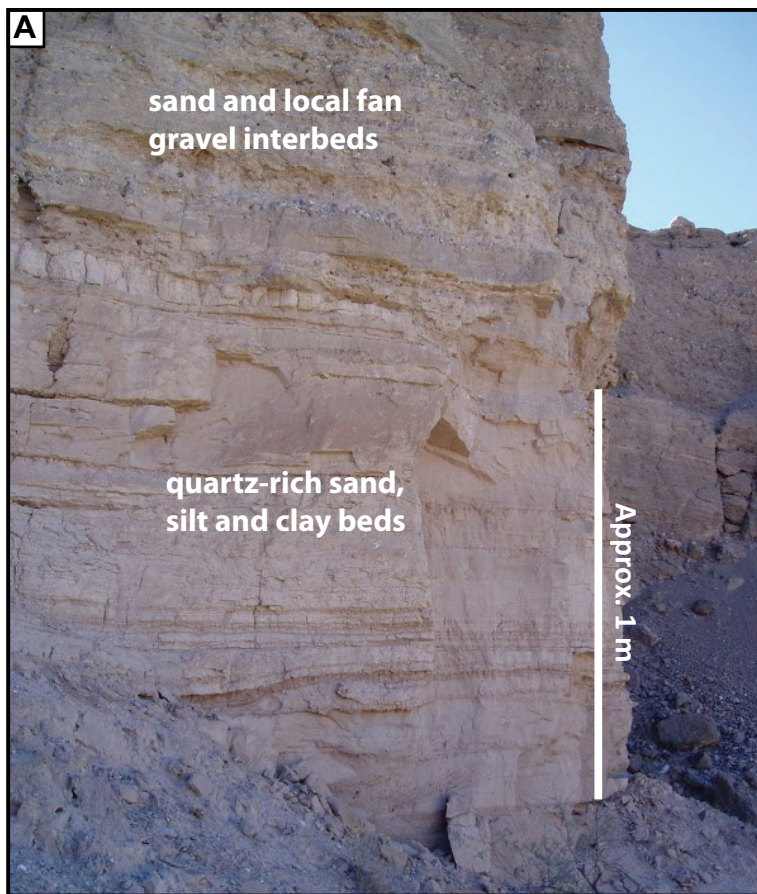
the level of the eroding outlet. After the maximum lake water level was attained, the outlet through the Topock paleodivide likely lowered in complex increments related to hydraulic erosion, mass wasting, and the influence of locally derived detrital sediment on outlet abrasion. Paleolake Mohave filled with sediment as the outlet lowered, and the river delta prograded southward through CV and MV, gradually expanding a sandy subaerial delta and diminishing the size and volume of the lake. There almost certainly would have been cannibalization of the early delta deposits in northern CV as the lake level dropped and the river feeding the lake incised (Fig. 4). Once the delta top reached the elevation of the lowering outlet, the lake was succeeded by a through-flowing river. At the very termination of paleolake Mohave, the river presumably flowed within a broad floodplain on top of Bouse deposits in the valley reaches and through a narrow canyon with a much steeper gradient in the Topock spillover. After the demise of paleolake Mohave, the outlet may have been eroded more aggressively as the river entrained bedload sediment stored in the former lake basin, resulting in substantial erosion of Bouse deposits (e.g., Meek, 1989).

BULLHEAD ALLUVIUM—UNEQUIVOCAL EVIDENCE FOR THE THROUGH-FLOWING COLORADO RIVER

The Bullhead alluvium is a complex deposit of fluvial sand, gravel, and (rare) mud that is unequivocally associated with the through-flowing Colorado River (Howard et al., 2015). Gravel in the unit is moderately to strongly polymictic, subangular to very well rounded, and planar to elaborately cross-stratified. Within the gravel, clast diversity generally appears to increase upsection, with more locally derived materials from Miocene fanglomerate deposits low in the section and very diverse resistant gravel clasts higher in the section. The thickness of gravel layers varies substantially; some exposures contain many meters of bedded gravel. Sand is more common than gravel in the Bull-head alluvium. Sand beds typically are <1–2 m thick, vary from tabular to elaborately cross-bedded, and are generally gray to buff colored with local oxidized yellow and orange layers or pockets (Fig. 10B). Petrified and subpetrified wood has been found in a number of localities, commonly associated with zones of oxidized (rusty) sand. Outcrops showing alternating sand and gravel layers are fairly common. Cohesion of both sand and gravel beds varies greatly;
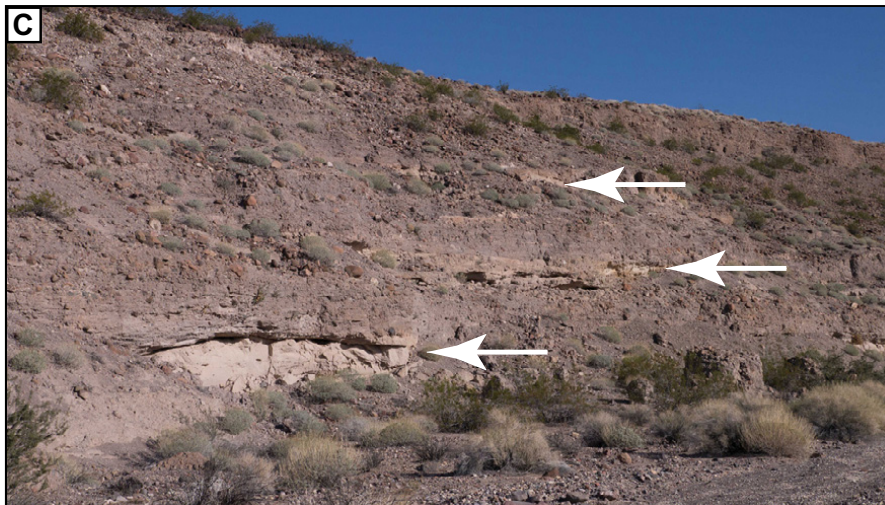
Figure 10. Bullhead gravel and sand from the Tyro Wash section in southern Cottonwood Valley. (A) The Tyro Wash section is dominated by thick tabular beds of cross-stratified rounded cobbles and boulders, and elaborately cross-bedded sand and finer gravel beds. The vertical section here is 45 m thick, and is part of a composite section that ranges from ~200 to 420 m above sea level (asl) in Cottonwood Valley. (B) Moderate close-up of the western end of the section shows complexly interbedded sands and rounded gravel beds typical of the Bullhead alluvium. (C) Tan quartz-rich river sand beds (white arrows) interfingered with darker tributary fan gravel beds farther upsection and away from the valley axis.

some beds are strongly cemented and others are weakly cohesive. We have found tabular beds of silt and clay in the Bullhead alluvium away from the valley axis. Overall, the Bullhead alluvium is a very complex fluvial deposit with numerous stratigraphic discontinuities, but to date we have not recognized strong paleosols or laterally continuous and obvious erosion surfaces suggestive of major hiatuses.

The base of the Bullhead alluvium is inset deeply within, and in some areas below, remnants of the Bouse Formation. In CV, Bullhead deposits are exposed along the margin of modern Lake Mohave at 195 m asl at a number of localities, including fairly far north along the lake shore (Fig. 11). Toward the valley margins, Bullhead deposits are found as high as 420 m asl. The lowest Bullhead deposits obviously are beneath the lake, but a few hundred meters away from the modern lake margin they are exposed over erosional contacts with bedrock and various pre-Bouse sedimentary units. Some of these contacts are along obvious paleochannel forms. The thickest nearly continuous outcrops of Bullhead alluvium are exposed along and in the immediate vicinity of Tyro Wash, where the base of the section is at 195 m asl and the highest intact deposits are exposed to 390 m asl with gravel lags reaching to ~420 m. This section also contains a sequence of tabular beds of river gravel as thick as 15 m and interbedded quartz-rich river sand and tributary gravel beds (Fig. 10; House et al., 2008b).

In MV, Bullhead alluvium outcrops are exposed as low as 150 m asl along the modern Colorado River and as high as 400 m asl on the Black Mountains piedmont (Fig. 11). Below ~300 m asl, Bullhead deposits are very common on the piedmont, and interfingering layers of river deposits and tributary fan deposits are evident at several localities. Tributary fan depos-

Figure 11. Examples of Bullhead alluvium. (A) Well-rounded, lithologically diverse river gravel lag on the Black Mountain piedmont at 400 m above sea level (asl), northern Mohave Valley. Clasts in the foreground range from pebbles to small cobbles. (B) Coarse rounded gravel on an approximately 2.5-m-high pedestal in Lake Mohave (195 m asl) in Cottonwood Valley. (C) Moderately indurated, cross-stratified, quartz-rich sand and rounded gravel at river level (150 m asl) near Fort Mohave in northern Mohave Valley (note woman and dogs for scale). Photo locations are shown on Figure 12 where corresponding elevations (A: 400 m; B: 195 m; and C: 150 m) are listed.

its dominate above ~300 m, but thin layers of rounded river gravel and quartz-rich sand interbedded with fan deposits are present as high as 400 m asl on the piedmont. Three outcrops of the 4.1 ± 0.5 Ma tuff of Artists Drive (Knott and Sarna-Wojcicki, 2001; House et al., 2008b) overlie fine gravel of tributary fans that were graded to the Colorado River floodplain at elevations ranging from 365 to 390 m asl. These fan deposits were subsequently onlapped by river sand and gravel deposits when the Colorado River reached the maximum level of aggradation at ~390–400 m asl, shortly after deposition of the tephra (House et al., 2005, 2008b). Thus, the highest level of early Colorado River aggradation in northern and central MV was ~150 m below the maximum inundation level of paleolake Mohave, and ~40 m below the highest levels of clastic Bouse deposition.

The elevation of the base of the Bullhead alluvium is at or below the modern valley floor, but the minimum elevation of Bullhead deposits is poorly constrained in both valleys. Well-log data from the southern end of MV describe the contact between Colorado River deposits overlying Bouse deposits at depths of 43–50 m below the floodplain or ~100 m asl (Metzger and Loeltz, 1973). This depth is broadly in accord with a profile connecting the bases of Hoover and Parker Dams, both of which are on bedrock deep below the historical river grade (Berkey, 1935). The Colorado River deposits in the subsurface may be Bullhead alluvium or younger deposits associated with deep erosion by the river in the early to middle Quaternary, so we infer that the base of the Bullhead alluvium in these valleys is between 100 and 150 m asl.

Based on the minimum and maximum elevations of Bullhead deposits, they represent a major episode of aggradation that resulted in the deposition of 250–300 m of fluvial sediment in MV and CV in the early Pliocene. Evidence for this major period of Colorado River aggradation in the early Pliocene is found at many locations along the river, from south of Yuma to the mouth of the Grand Canyon (Howard et al., 2015). Aggradation was presumably driven by a very large supply of bedload sediment to the river, which may have been caused by high rates of mainstem and tributary erosion in the developing modern Grand Canyon and on the Colorado Plateau. During this period of aggradation the valley axis was almost certainly a very broad braid plain, which likely widened as the river approached its maximum level of aggradation. Concurrent and inevitable tributary fan aggradation driven by the rising local base level is indicated by exposures of interfingering river and tributary deposits (Fig. 10C), but it is likely that the early Colorado River supplied the bulk

of the sediment filling the valleys. Together, these sources filled MV and CV with several hundred cubic kilometers of sediment after Bouse deposition and before 4–3.5 Ma.

A period of deep erosion must have occurred shortly after Bouse deposition to provide the space in these valleys that was filled by Bullhead aggradation. In southern and central MV, this involved deep erosion into, but not beneath, Bouse deposits to 100–150 m asl (Fig. 13). Due to the relatively high pre-Bouse valley floor in CV, the pre-Bullhead valley axis was eroded 100–150 m below the base of Bouse deposition into older fanglomerate, axial valley deposits, and bedrock. The fact that Bullhead deposits filled so much of these valleys requires that a large volume of Bouse sediment was removed by erosion prior to Bullhead aggradation, thus fairly soon after they were deposited.

INTERPRETATION OF THE EARLY EVOLUTION OF THE LOWER COLORADO RIVER

We present a general scenario for the early development of the LCR based primarily on the stratigraphic and geomorphic relationships described in MV and CV. In addition, we consider the implications of these relationships for the downstream development of the river and the alternative interpretations of Bouse deposition in the PBC basin as representing an estuarine or lacustrine environment. The elevations of various paleodivides and deposit elevation ranges for Bouse and Bullhead deposits used in this reconstruction are different from others presented previously and in this volume (Spencer and Patchett, 1997; Turak, 2000; Spencer et al., 2008, 2013; McDougall and Miranda Martínez, 2014). Our estimates for paleodivide elevations are based on the highest Bouse outcrops found upstream from the paleodivides. The lowest elevations of Bouse and Bullhead deposits shown in various valleys are based on previous work (Metzger et al., 1973; Metzger and Loeltz, 1973), our own recent field observations in MV, CV, and the Chemehuevi Valley–Lake Havasu basin, and a recent compilation of Bullhead elevations by Howard et al. (2015).

Pre-Bouse Landscape

In the latest Miocene, MV and CV drained to separate depocenters. CV was perched above MV, with the relatively low Pyramid paleodivide between them. In southern CV, alluvial fans sloped west and east toward an axial fluvial system that drained north to a depocenter in central CV at ~300 m asl. The valley axis in northern MV sloped south, and alluvial fans all around

the valley sloped inward toward the valley axis and the basin depocenter in southern and central MV at ~50–100 m asl. MV was a regional low, with Sacramento Valley to the east and Piute Valley to the west draining into it. MV and Chemehuevi Valley were separated by a higher range of bedrock hills, the Topock paleodivide, extending southeast to northwest between the Mohave Mountains and the Chemehuevi Mountains. The floor of Chemehuevi Valley to the south was probably slightly higher than the floor of MV (100–135 m asl).

Development, Evolution, and Demise of the Bouse Lakes

When river water arrived from the north sometime after 5.6 Ma, the axis of CV quickly filled with a relatively shallow lake before spilling over the Pyramid paleodivide down into MV (1 and 2 in Fig. 14). This spillover resulted in rapid erosion of the divide and deposition of the coarse Pyramid gravel in northernmost MV. As river water continued to enter CV from the north, the divide was submerged and both valleys became part of the ~150-km-long, ~500-m-deep, ~700 km^3 volume paleolake Mohave. Carbonate deposits found above 530 m asl in 6 widely spaced upper piedmont areas, including the southernmost and northernmost outcrops yet found in these valleys, are consistent with an essentially flat water surface that has not been detectably tilted in the past 5 m.y. We obviously do not know what the average annual influx of Colorado River water was ca. 5 Ma, but detrital zircon analysis indicates that it drained a large watershed generally similar to the modern Colorado River (Kimbrough et al., 2015). If we assume an average annual water influx similar to the modern Colorado River (~15–20 km^3/yr; Spencer et al., 2008; U.S. Bureau of Reclamation, 2012) and a modern evaporation rate appropriate for this region (1–2 m/yr), this large, deep lake would have filled completely in <100 yr (Spencer et al., 2008). We have found many examples of basal carbonate draped on well-preserved paleoalluvial fan surfaces and limited evidence of interaction between tributary fan-delta deposits and lake deposits (Figs. 7A, 7B, 7E); these relationships are consistent with rapid lake-level rise.

The lake level began to lower when the Topock paleodivide was overtopped and water spilled south into paleolake Havasu in Chemehuevi Valley (3 in Fig. 14). Evaporation from the paleolake Mohave might have significantly decreased outflow during warm parts of the year and when water influx rates were low, but generally the rate of overflow would have been close to the influx of river water. During times of high

river flow, the rate of outflow would have been roughly the same as the influx rate, and during these times erosion rates could have been fairly high due to the steep slope into Chemehuevi Valley (initially, ~400 m fall in a few kilometers, decreasing to ~200 m as paleolake Havasu filled). The erosion rate also depended on the resistance of materials forming the divide, and erosion was almost certainly episodic due to varying flow rates and substrate resistance.

As the Topock outlet was eroded, paleolake Mohave filled with a sequence of prograding delta deposits composed of clay, silt, and quartz-rich sand supplied primarily by the Colorado River (4 in Fig. 14). The volume of the lake decreased as the water surface lowered and sediment filled the valley. As long as the lake existed, however, all but the finest suspended sediment was stored in it, so the system would have supplied primarily water and solutes with very little siliciclastic sediment to downstream basins. Paleolake Mohave ceased to exist when the level of sedimentation at the south end of MV reached that of the lowering divide (5 in Fig. 14). Based on the general distribution of siliciclastic deposits and the upward transition from quartz-rich sand to gravelly tributary alluvial fan deposits exposed in Secret Pass Canyon, we infer that the cross-over elevation in southern Mohave valley was ~400 m asl. The rate at which the lake filled with sediment depended on the sediment influx, but assuming the modern sedimentation rate measured for the Colorado River in Lake Powell and Lake Mead (~0.1 km^3/yr; Ferrari, 1988, 2008), the basin would have filled with sediment up to that level in ~2500–7500 yr. Thus, the entire lifespan of the large and deep paleolake Mohave was likely quite brief.

Initial Post-Bouse Erosion and Its Relationship with Downstream Basins

Continued lowering of the Topock outlet after the demise of paleolake Mohave resulted in incision of the river in MV and CV and recycling of fine siliciclastic Bouse sediment into downstream basins. The immediate base-level control was the level of water and ultimately of sediment accumulation in paleolake Havasu. This basin is relatively small, however, so it would have quickly filled with water when paleolake Mohave spilled over, and then in turn would have spilled over into the PBC basin to the south. After the demise of paleolake Mohave, paleolake Havasu would have filled with sediment fairly quickly and ceased to be a lake. This area likely transitioned into being the northern part of a delta feeding into the much larger PBC basin downstream (6 in Fig. 14).
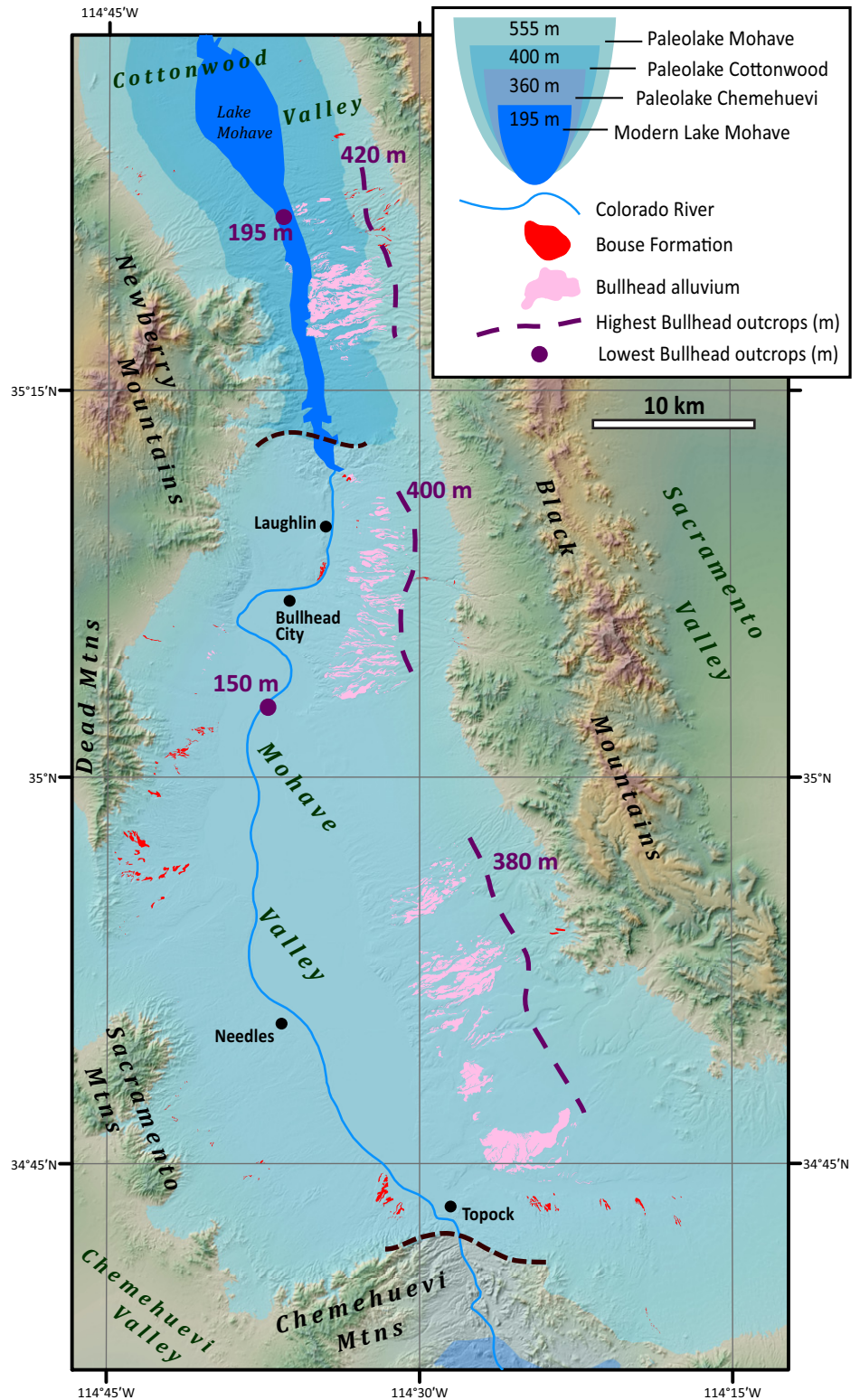
Figure 12. Lateral and vertical extent of the Bullhead alluvium. Map of Mohave and Cottonwood Valleys showing extent of mapped Bullhead alluvium in pink; mapped Bouse deposits are in red. Dashed purple lines encompass the highest Bullhead outcrops in various parts of these valleys. Minimum and maximum elevations of the outcrops are noted with purple numbers.
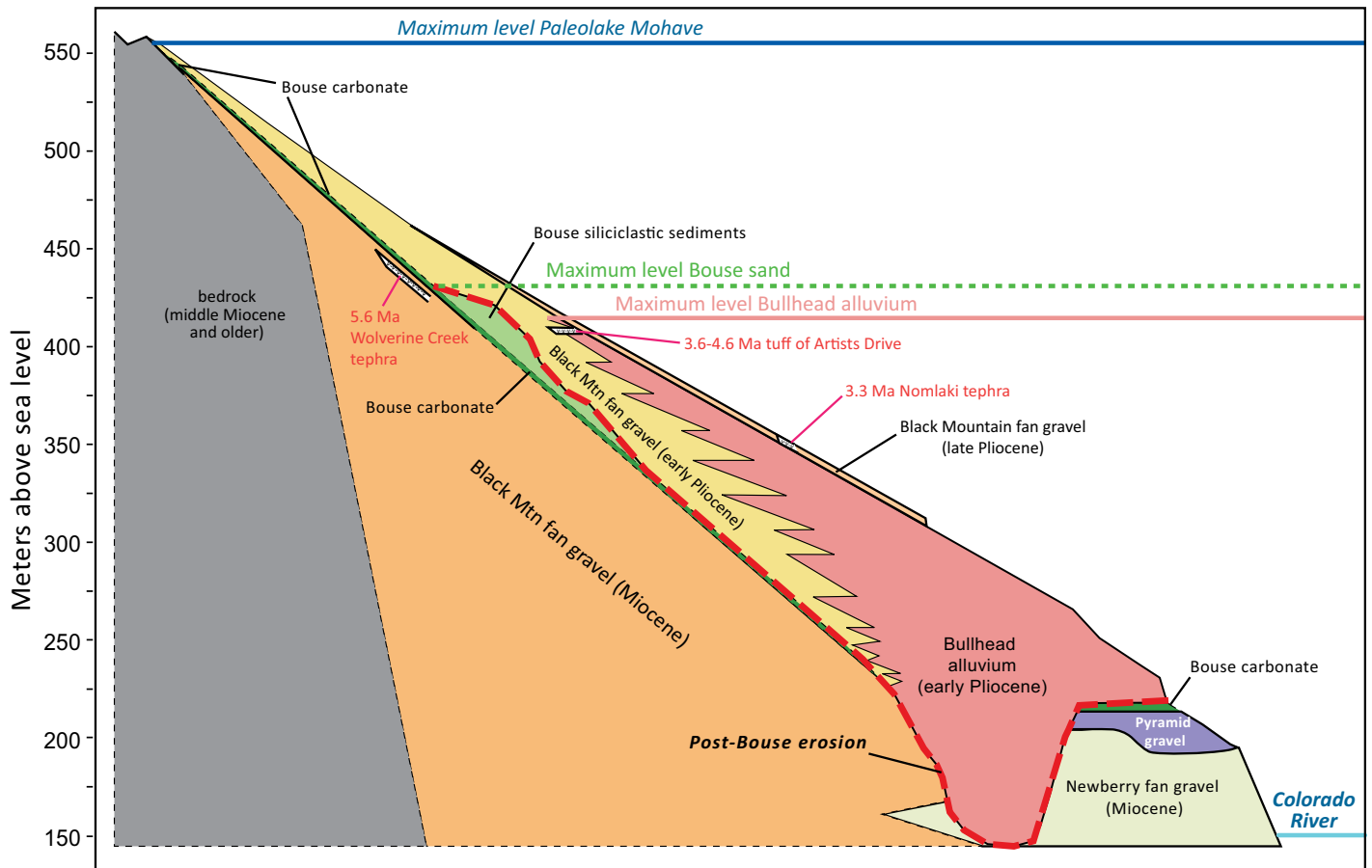
Figure 13. Schematic diagram of the valley axis and Black Mountain piedmont in northern Mohave Valley. Levels of maximum Bouse inundation (blue line), maximum Bouse sand deposition (green dashed line), post-Bouse, pre-Bullhead erosion (red line), and maximum Bullhead aggradation (tan line) are shown against preserved local and river deposits.

The water level in the PBC basin was base level for the river system for a much longer interval, and thus controlled the minimum level to which the river could erode bedrock divides and sedimentary basins upstream. This is true whether the PBC basin was gradually inundated by a large lake fed by the Colorado River, or was inundated by an estuary connected to the Gulf of California prior to the arrival of Colorado River water. However, the base-level implications of these scenarios are quite different.

If the PBC basin was a lake (paleolake Blythe) that filled gradually with water supplied by the Colorado River, base level would have initially been quite low, probably below sea level in the deepest part of the basin (based on data and interpretations from Metzger et al., 1973). Base level would have risen as paleolake Blythe filled with water (6 in Fig. 14). Following the arguments presented earlier, the Colorado River would have filled the lowest parts of the modern Colorado River valley quickly, but because of the large, presumably shallow areas of paleolake Blythe

through much of the eastern Mojave Desert, thousands of years may have been required to fill with PBC basin with water (Spencer et al., 2008, 2013). Potential river erosion upstream in Chemehuevi Valley, MV and CV would have been controlled by the rate of lowering of the nascent Parker, Topock, and Pyramid bedrock canyon reaches while the regional base level was below them. However deeply these reaches were eroded while the level of paleolake Blythe was low, they would have back-filled to a level above 330 m asl as paleolake Blythe rose to a maximum of 330 m asl.

If the PBC basin was an estuary, then the highest Bouse deposits in this basin that are currently ~330 m asl were at sea level in the latest Miocene to early Pliocene, which was probably 15–30 m higher than modern sea level in this region (Spencer et al., 2013). Water level in the estuary would not have been significantly affected by the arrival of Colorado River water and thus would have served as a stable base level for the developing river system. In this

scenario, the river upstream from the north end of the estuary could not have eroded below what was then sea level (now 330 m asl) for as long as the estuary existed at that level. In this scenario the entire LCR region would have had to have been uplifted by at least 300 m since Bouse deposition, and any incision below 330 m asl along the river valley upstream would have been associated with or driven by that uplift.

Deep Post-Bouse Erosion and Early Colorado River Aggradation

Subaerial deposits of the early Pliocene Bullhead alluvium and lesser amounts of tributary alluvial fan deposits filled broad swaths of both CV and MV from <150 to 420 m asl. Interfingering relationships between river gravel and sand and tributary gravel deposits exposed from the modern basin axis to high on piedmonts (Fig. 11C) indicate that tributary fan aggradation was forced by local base-level rise associated with river aggradation. Since these valleys were filled
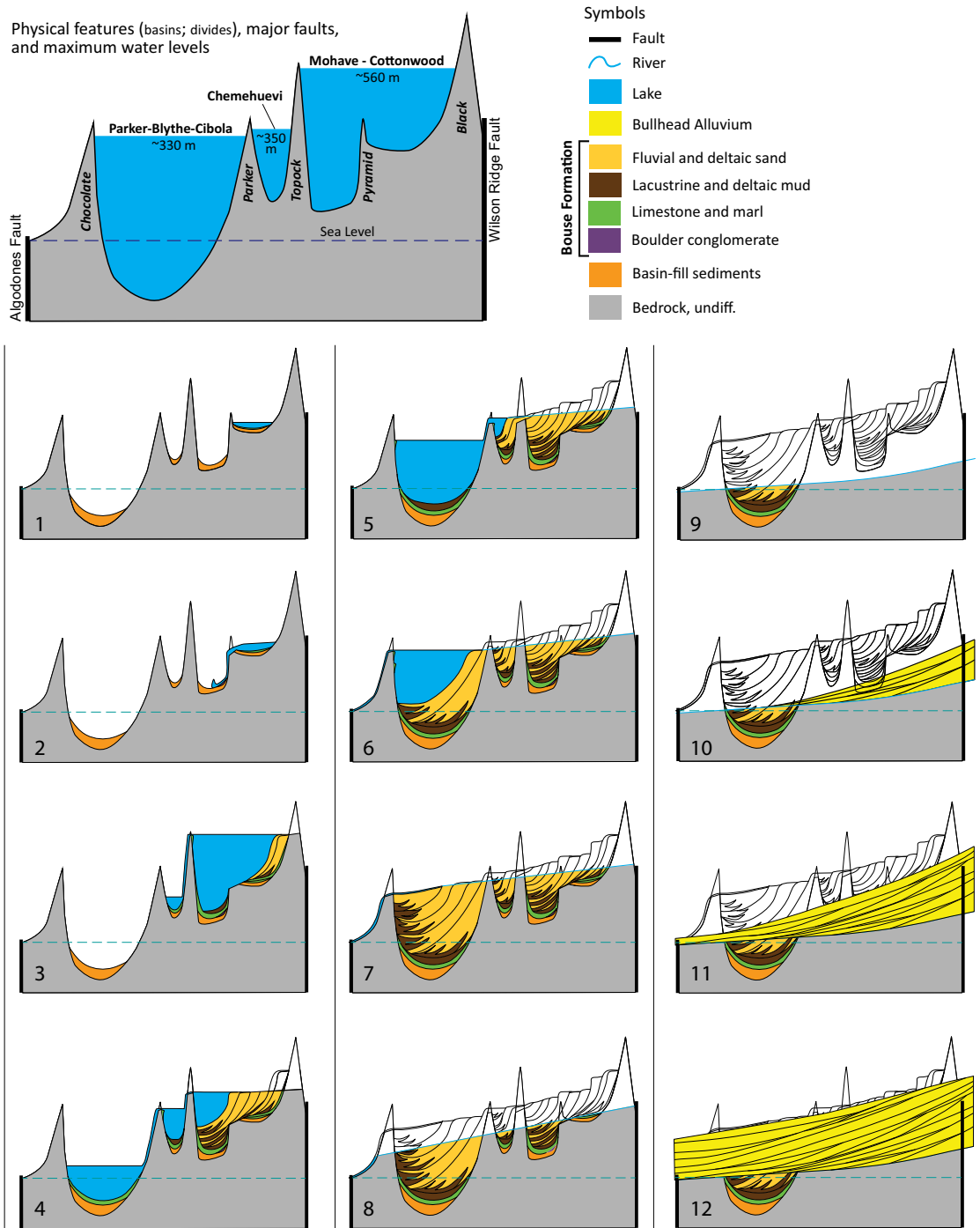
Figure 14. Schematic north-south transects illustrating the fluviolacustrine model of the development of the Lower Colorado River (undiff.—undifferentiated). (1) Pre-Bouse closed basins and paleodivides. Paleolake Cottonwood forms as Colorado River first enters from the north. (2) River-fed paleolake Cottonwood expands and spills into Mohave Valley and erodes the Pyramid paleodivide. (3) Paleolake Mohave, full of water, spills to the south over the Topock paleodivide into paleolake Havasu; a delta progrades in Cottonwood Valley; carbonate deposition occurs in paleolake Havasu. (4) Paleolake Mohave is mostly filled with sediment as Topock spillover is lowered; sediment-starved, carbonate-bearing water is supplied to downstream basins. (5) Paleolake Mohave is gone, Topock outlet is partially eroded, paleolake Havasu is partially filled with sediment, and paleolake Blythe is partially filled with carbonate-bearing water, but no siliclastic sediment. (6) Paleolake Havasu is gone, delta building occurs in the northern end of paleolake Blythe, and there is incipient spilling to Gulf of California. (7) The demise of paleolake Blythe occurs as sedimentation reaches outlet level; thick Bouse deposits fill the Parker-Blythe-Cibola basin. (8) There is continued lowering of Chocolate spillover, erosion of Bouse basins, and bedrock reaches upstream. (9) The base profile for Bullhead aggradation is created by the culmination of river incision into Bouse sediments and bedrock. (10–12) Representations of progressive Bullhead aggradation through the lower Colorado River Valley (for a more thorough discussion, see Howard et al., 2015).

with Bouse siliciclastic deposits prior to this, deep incision and pervasive basin erosion must have occurred soon after Bouse deposition in order to create the space that was filled by Bullhead aggradation. The presence of the Lawlor Tuff in Bouse deposits at ~300 m asl implies that this incision is younger than 4.8 Ma, as the developing LCR drained to the PBC water body and could not have eroded below the water surface at that time. Incision occurred prior to the beginning of Bullhead aggradation, which was ongoing farther upstream by 4.4 Ma (Faulds et al., 2001) and culminated in this area ca. 4–3.5 Ma.

Bouse deposits, locally underlying deposits, and bedrock reaches must have been rapidly and deeply eroded to create space for the voluminous Bullhead and tributary deposition in MV and CV and elsewhere along the LCR (Howard et al., 2015). Some erosion of high Bouse deposits likely occurred as paleolake Mohave evolved and the water surface gradually lowered. Much more erosion certainly occurred as the river was draining into Chemehuevi Valley and the PBC basin. Deep erosion in the basin axes prior to Bullhead aggradation, however, requires that base level for MV and CV fell to below 100–150 m asl soon after 4.8 Ma. This in turn requires that the PBC basin drained and was eroded to a level well below 150 m asl soon after 4.8 Ma, allowing for lowering of bedrock reaches and deep and pervasive erosion of large volumes of Bouse sediment upstream prior to Bullhead aggradation.

This incision would be an expected consequence of base-level fall associated with filling and spillover of paleolake Blythe to the Gulf of California: (1) filling of a topographically complex lake with water over 10,000 yr or more, because of the large volume and especially surface area (Spencer et al., 2008, 2013); (2) accumulation of river delta sediment in the valley of the modern Colorado River between Parker and Cibola after the demise of paleolake Mohave, as the lake level rose and water spread into the eastern Mojave Desert area (6 in Fig. 14); (3) overtopping of the Chocolate Mountains paleodivide and the beginning of erosional lowering of the spillway; sediment continued to accumulate in the LCR valley as long as the lake persisted; (4) demise of paleolake Blythe when the level of sediment accumulation rose to the level of the eroding spillway (7 in Fig. 14); (5) fairly rapid incision of the Chocolate Mountains bedrock reach toward a new, dramatically lower base level—early Pliocene sea level (8 in Fig. 14); (6) deep erosion of the PBC basin and upstream basins driven by this base-level fall, controlled by the rate of incision of the bedrock reaches (9 in Fig. 14); the incipient LCR erodes to levels similar to or lower than the

modern river grade; (7) Colorado River aggradation (Bullhead alluvium) caused by very high sediment supply filled much of the erosional topography, proceeding from upstream to downstream (10–12 in Fig. 14).

This scenario is broadly similar to a model of development of the initial Colorado River profile presented by Karlstrom et al. (2007). Because the elevation range of the Bullhead alluvium is at or below the modern river grade, however, this scenario does not require regional uplift or warping from the Yuma area to CV in the past 5 m.y. Local deformation, such as continued subsidence of some basins along the LCR after Bouse or Bullhead deposition, would have primarily affected the modern elevations of the deepest elements of these deposits (Howard et al., 2015). For example, in MV the primary uncertainty associated with possible post-Bouse deformation is the elevation of the floor of valley at the time of Bouse deposition. All of the data points we use to estimate the maximum elevation of paleolake Mohave are high on piedmonts, at or near mountain fronts, and far from the area of possible subsidence. In the PBC basin, the fact that the lowest unit B (equivalent to Bullhead alluvium) Colorado River deposits interpreted from well cuttings are below modern sea level (Metzger et al., 1973) indicates subsidence during and after deposition of the Bullhead alluvium. As in the valleys farther north, however, all of the data used to infer the maximum water surface associated with Bouse inundation (Spencer et al., 2013) are located on bedrock or high on alluvial piedmonts, quite distant from the valley axis where subsidence has occurred.

If the Bouse Formation in the PBC basin was deposited in an estuary that was part of the northern Gulf of California ca. 5 Ma, there is no intrinsic mechanism to generate the necessary upstream erosion shortly after that time. Upstream incision could not have occurred below what is now 300–330 m asl as long as the estuary existed, as the early LCR would not have been able to incise below what was then sea level in this relative framework. Thus, rapid uplift of the entire region to something close to modern elevations very soon after the cessation of Bouse deposition would have been necessary to drive the deep incision that predates Bullhead aggradation. Post-Bouse local subsidence of axial valleys as described here would not have driven significant upstream erosion, because the valleys would have quickly filled with river sediment as they subsided. Uplift of all or parts of the PBC basin only (not extending to areas to the north) could have driven river incision in the affected areas, but would not have caused incision upstream. Gradual regional uplift of a former PBC estuary and upstream valleys over

the past 5 m.y. (e.g., Lucchitta, 1979) would not have caused, and is not consistent with, the dramatic early Pliocene incision evident in MV and CV. Because of the rapid and broad uplift required to drive upstream river incision, we argue that this scenario is unlikely.

Hybrid marine and lacustrine scenarios (McDougall and Miranda Martínez, 2014; K. Karlstrom, 2014, written commun.) present some interesting possible implications for the early evolution of the LCR. One scenario is that some of the lower part of the Bouse Formation records a late Miocene marine incursion that predates the arrival of the Colorado River. This marine embayment might have then been isolated north of the Chocolate Mountains by uplift along the developing San Andreas fault system prior to the arrival of Colorado River water and sediment. Continued uplift of the Chocolate Mountains to above 330 m asl prepared the area to contain paleolake Blythe when the Colorado River arrived. This scenario is attractive in that it seems to reconcile the paleontology, dating, and geomorphology of the system. There are significant unresolved issues, however, such as the lack of evidence for regional desiccation when the marine embayment was isolated, the fact that the siliciclastic deposits that contain marine forams appear to be very similar to those upstream in Chemehuevi Valley, MV and CV, and the fact that foram-bearing deposits are stratigraphically above the basal carbonate, as is the case farther north.

Alternatively, the forams might have lived in a deep part of the estuary that existed in the late Miocene and earliest Pliocene, and the Colorado River entered from the north in the earliest Pliocene. This is essentially consistent with interpretations that the PBC Bouse was deposited in estuarine to marine conditions, and Colorado River built a delta into it (i.e., Buising, 1990). As described here, this model requires surprisingly rapid uplift of the entire LCR to provide vertical space for the pre-Bullhead incision that occurred upstream, and we believe that is a major liability.

Latest Miocene to early Pliocene sea level in the PBC basin could not have been at what is now 110 m asl (the elevation of the foram-bearing strata) simultaneously with deposition of the Bouse delta deposits southeast of Parker at 300 m asl. There is no possible paleodivide to separate these areas, thus the body of water was continuous. In addition, the Lawlor Tuff records a water surface at 300 m asl on the north flank of the Chocolate Mountains, south of the foram-bearing Bouse deposits. We do not see that hybrid marine-lacustrine interpretations provide any middle ground for possible regional uplift unless uplift predated the development of the LCR.

CONCLUSIONS

The latest Miocene–early Pliocene deposits in CV and MV and the paleolandscapes on which they were deposited provide critical insights into the early development of the lower Colorado River. When initial Colorado River water entered the region from the north sometime after 5.6 Ma, these valleys were separate depocenters with a low divide between them; the floor of CV was perched ~200 m above the adjacent MV. Colorado River water filled the axis of CV with a relatively small lake that soon spilled southward into MV. Both valleys were filled by the large, deep paleolake Mohave. When the surface of paleolake Mohave approached ~560 m asl, it spilled over the southern Topock paleodivide and into Chemehuevi Valley, and soon into the much larger PBC basin. Paleolake Mohave continued to fill with fluviolacustrine sediment supplied by the Colorado River for several thousand years as the Topock outlet was lowered by erosion, the lake water volume decreasing until the lake was filled with sediment to the level of the spillover. During the time paleolake Mohave was filling with sediment, relatively sediment-free, carbonate-rich water was feeding downstream basins.

Continued lowering of the Topock outlet after the demise of paleolake Mohave drove some incision of the Colorado River in MV and CV, adding recycled sediment from these valleys to incoming sediment from the upstream watershed. The level to which the Topock bedrock canyon and upstream valley bottoms could be eroded depended on regional base level. If the large PBC basin was a large lake gradually filled by the Colorado River, then base level initially was quite low, but would have risen to its maximum at 330 m asl ca. 4.8 Ma, when the Lawlor Tuff was deposited in shallow Bouse water. If the PBC basin was an estuary, the water level would not have been significantly affected by the arrival of Colorado River water, and the river upstream would have been constrained to be above what was then sea level and is now 330 m asl for as long as the estuary existed.

There is clear evidence for deep, pervasive erosion in MV and CV after Bouse deposition and prior to major early Pliocene Colorado River aggradation, as the Bullhead alluvium filled valley axes that had formerly been occupied by Bouse deposits. This erosion requires that regional base level fell to below 150 m asl soon after 4.8 Ma. Base-level fall such as this is intrinsic in the lake filling and spilling model, wherein paleolake Blythe filled with river water and spilled over the Chocolate Mountain divide, establishing a new and much lower base level for the Colorado River system. Deep incision of

the former lake deposits and upstream bedrock divides would be expected after the southernmost lake filled with sediment and ceased to exist, limited only by the elevation of sea level in the early Pliocene. Such base-level fall is not intrinsic to the estuary model for the PBC basin. In this case, the entire region would have to have been uplifted rapidly after 4.8 Ma to permit the deep upstream incision. Gradual regional uplift of a former PBC estuary and upstream valleys since 5 Ma would not have caused, and is not consistent with, dramatic early Pliocene incision in the LCR Valley.

REFERENCES CITED

Berkey, C.P., 1935, Parker Dam Memorandum No. 1: On geologic features of Parker Dam Site: U.S. Bureau of Reclamation, 45 p.

Blackwelder, E., 1934, Origin of the Colorado River: Geological Society of America Bulletin, v. 45, p. 551–566, doi:10.1130/GSAB-45-551.

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 LCR: Journal of Geophysical Research, v. 95, p. 20,111–20,132, doi:10.1029/JB095iB12p20111.

Crossey, L.C., and 10 others, 2015, The importance of groundwater in propagating downward integration of the 6–5 Ma Colorado River System: Geochemistry of springs, travertines and lacustrine carbonates of the Grand Canyon region over the past 12 million years: Geosphere, v. 11, doi:10.1130/GES01073.1 (in press).

Dorsey, R.J., Fluette, A., McDougall, K., Housen, B.A., Janecke, S.U., Axen, G.J., and Shirvell, C.R., 2007, Chronology of Miocene–Pliocene deposits at Split Mountain Gorge, southern California: A record of regional tectonics and Colorado River evolution: Geology, v. 35, p. 57–60, doi:10.1130/G23139A.1.

Ferrari, R.L., 1988, 1986 Lake Powell survey: U.S. Bureau of Reclamation Technical Service Center Report, 67 p.

Ferrari, R.L., 2008, 2001 Lake Mead sedimentation survey: U.S. Bureau of Reclamation Report REC-ERC-88–6, 101 p.

Faulds, J.E., Wallace, M.A., Gonzales, L.A., and Heizler, M.T., 2001, Depositional environment and paleogeographic implications of the late Miocene Hualapai Limestone, northwestern Arizona and southern Nevada, *in* Young, R.A., and Spamer, E.E., eds., The Colorado River: Origin and evolution: Grand Canyon, Arizona, Grand Canyon Association Monograph 12, p. 81–88.

Faulds, J.E., House, P.K., Pearthree, P.A., Bell, J.W., and Ramelli, A.R., 2004, Preliminary geologic map of the Davis Dam quadrangle and eastern part of the Bridge Canyon quadrangle, Clark County, Nevada and Mohave County, Arizona: Nevada Bureau of Mines and Geology Open-File Report 03-5, scale 1:24,000.

House, P.K., and Faulds, J.E., 2009, Preliminary geologic map of the Spirit Mtn. NW quadrangle, Clark County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 09-6, scale 1:24,000.

House, P.K., Howard, K.A., Bell, J.W., and Pearthree, P.A., 2004, Preliminary geologic map of the Arizona and Nevada parts of the Mt. Manchester quadrangle: Nevada Bureau of Mines and Geology Open-File Report 04-04, scale 1:24,000.

House, P.K., Pearthree, P.A., Howard, K.A., Bell, J.W., Perkins, M.E., and Brock, A.L., 2005, Birth of the lower Colorado River—Stratigraphic and geomorphic evidence for its inception near the conjunction of Nevada, Arizona, and California, *in* Pederson, J., and Dehler, C.M., eds., Interior western United States: Geological Society of America Field Guide 6, p. 357–387, doi:10.1130/2005.fld006(17).

House, P.K., Brock, A.L., and Pearthree, P.A., 2008a, Preliminary geologic map of late Cenozoic deposits in the Spirit Mtn. SE quadrangle, Clark County, Nevada: Nevada Bureau of Mines and Geology Open-File Report 08-3, scale 1:24000.

House, P.K., Pearthree, P.A., and Perkins, M.E., 2008b, Stratigraphic evidence for the role of lake spillover in the birth of the lower Colorado River near the southern tip of Nevada, *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. 335–353, doi:10.1130/2008.2439(15).

Howard, K.A., Nielson, J.E., Wilshire, W.G., Nakata, J.K., Goodge, J.W., Reneau, S.L., John, B.E., and Hansen, V.L., 1999, Geologic map of the Mohave Mountains area, Mohave County, western Arizona: U.S. Geological Survey Map I-2308, scale 1:48,000.

Howard, K.A., John, B.E., Nielson, J.E., Miller, J.M.G., and Wooden, J.L., 2013, Geologic map of the Topock 7.5′ quadrangle, Arizona and California: U.S. Geological Survey Map I-3236, 60 p.

Howard, K.A., House, P.K., Dorsey, R.J., and Pearthree, P.A., 2015, River-Evolution and Tectonic Implications of a Major Pliocene Aggradation on the Lower Colorado River, the Bullhead Alluvium: Geosphere, v. 11, doi:10.1130/GES01059.1 (in press).

Karlstrom, K.E., Crow, R.S., Peters, L., McIntosh, W., Raucci, J., Crossey, L.J., Umhoefer, P., and Dunbar, N., 2007, $^{40}Ar/^{39}Ar$ and field studies of Quaternary basalts in Grand Canyon and model for carving Grand Canyon: Quantifying the interaction of river incision and normal faulting across the western edge of the Colorado Plateau: Geological Society of America Bulletin, v. 119, p. 1283–1312, doi:10.1130/0016-7606(2007)119[1283:AAFSOQ]2.0.CO;2.

Kimbrough, D.L., Grove, M., Gehrels, G.E., Mahoney, J.B., Dorsey, R.J., Howard, K.A., House, P.K., Pearthree, P.A., and Flessa, K., 2011, Detrital zircon record of Colorado River integration into the Salton Trough, *in* Beard, L.S., et al., eds., CRevolution 2—Origin and evolution of the Colorado River system, Workshop abstracts: U.S. Geological Survey Open-File Report 2011-1210, p. 168–174, http://pubs.usgs.gov/of/2011/1210/.

Kimbrough, D.L., Grove, M., Gehrels, G.E., Dorsey, R.J., Howard, K.A., Lovera, O., Aslan, A., House, P.K., and Pearthree, P.A., 2015, Detrital zircon U-Pb provenance record of the Colorado River: Implications for late

Cenozoic drainage evolution of the American Southwest: Geosphere, v. 11, doi:10.1130/GES00982.1 (in press).

Knott, J.R., and Sarna-Wojcicki, A.M., 2001, Late Pliocene tephrostratigraphy and geomorphic development of the Artists Drive structural block, *in* Machette, M.N., et al., eds., Quaternary and late Pliocene geology of the Death Valley region: Recent observations on tectonics, stratigraphy, and lake cycles (Guidebook for the 2001 Pacific Friends of the Pleistocene Fieldtrip): U.S. Geological Survey Open-File Report 01-0051, p. C105–C111.

Knott, J.R., Machette, M.N., Klinger, R.E., Sarna-Wojcicki, A.M., Liddicoat, J.C., Tinsley, III, J.C., David, B.T., and Ebbs, V.M, 2008, Reconstructing late Pliocene to middle Pleistocene Death Valley lakes and river systems as a test of pupfish (Cyprinodontidae) dispersal hypotheses, *in* Reheis 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. 1–16, doi:10.1130/2008.2439(01).

Lucchitta, I., 1972, Early history of the Colorado River in the Basin and Range Province: Geological Society of America Bulletin, v. 83, p. 1933–1948, doi:10.1130/0016-7606(1972)83[1933:EHOTCR]2.0.CO;2.

Lucchitta, I., 1979, Late Cenozoic uplift of the southwestern Colorado Plateau and adjacent LCR region: Tectonophysics, v. 61, p. 63–95, doi:10.1016/0040-1951(79)90292-0.

Lucchitta, I., McDougall, K., Metzger, D.G., Morgan, P., Smith, G.R., and Chernoff, B., 2001, The Bouse Formation and post-Miocene uplift of the Colorado Plateau, *in* Young, R.A., and Spamer, E.E., eds., The Colorado River: Origin and evolution: Grand Canyon, Arizona, Grand Canyon Association Monograph 12, p. 173–178.

Malmon, D.V., Howard, K.A., and Priest, S.S., 2009, Geologic map of the Needles 7.5′ quadrangle, California and Arizona: U.S. Geological Survey Map I-3062, scale 1:24,000, 31 p.

Malmon, D.V., Howard, K.A., House, P.K., Lundstrom, S.C., Pearthree, P.A., Sarna-Wojcicki, A.M., Wan, E., and Wahl, D.B., 2011, Stratigraphy and depositional environments of the upper Pleistocene Chemehuevi Formation along the lower Colorado River: U.S. Geological Survey Professional Paper 1786, 95 p.

McDougall, K., 2008, Late Neogene marine incursions and the ancestral Gulf of California, *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. 355–373, doi:10.1130/2008.2439(16).

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

Meek, N., 1989, Geomorphic and hydrologic implications of the rapid incision of Afton Canyon, Mojave Desert, California: Geology, v. 17, p. 7–10, doi:10.1130/0091-7613(1989)017<0007:GAHIOT>2.3.CO;2.

Meek, N., and Douglas, J., 2001, Lake overflow: An alternative hypothesis for Grand Canyon incision and the development of the Colorado River, *in* Young, R.A., and Spamer, E.E., eds., The Colorado River: Origin and evolution: Grand Canyon, Arizona, Grand Canyon Association Monograph 12, p. 199–204.

Metzger, D.G., 1968, The Bouse Formation (Pliocene) of the Parker-Blythe-Cibola area, Arizona and California: U.S. Geological Survey Professional Paper 600-D, scale 1:603,000, p. D126–D136.

Metzger, D.G., and Loeltz, O.J., 1973, Geohydrology of the Needles area, Arizona, California, and Nevada: U.S. Geological Survey Professional Paper 486-J, 54 p.

Metzger, D.G., Loeltz, O.J., and Irelan, B., 1973, Geohydrology of the Parker-Blythe-Cibola area, Arizona and California: U.S. Geological Survey Professional Paper 486-G, 130 p.

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

Morgan, L.A., and McIntosh, W.C., 2005, Timing and development of the Heise volcanic field, Snake River Plain, Idaho, western USA: Geological Society of America Bulletin, v. 117, p. 288–306, doi:10.1130/B25519.1.

Pearthree, 2007, Geologic map of the Needles NE 7.5′ quadrangle, Mohave County, Arizona: Arizona Geological Survey Digital Geologic Map DGM-45, scale 1:24,000, 15 p.

Pearthree, P.A., and House, P.K., 2005, Geologic map of the Davis Dam SE quadrangle, Mohave County, Arizona, and Clark County, Nevada: Arizona Geological Survey Digital Geologic Map DGM-45, scale 1:24,000.

Pearthree, P.A., Ferguson, C.A., Johnson, B.J., and Guynn, J., 2009, Geologic map and report for the proposed State Route 95 Realignment Corridor, Mohave County, Arizona: Arizona Geological Survey Digital Geologic Map DGM-65, scale 1:24,000, 47 p.

Poulson, S.R., and John, B.E., 2003, Stable isotope and trace element geochemistry of the basal Bouse Formation carbonate, southwestern United States: Implications for the Pliocene uplift history of the Colorado Plateau: Geological Society of America Bulletin, v. 115, p. 434–444, doi:10.1130/0016-7606(2003)115<0434:SIATEG>2.0.CO;2.

Reynolds, R.E., Faulds, J., House, P.K., Howard, K., Malmon, D., Miller, C.F., and Pearthree, P.A., 2007, Wild, scenic and rapid trip down the Colorado River trough: Desert Symposium field trip 2007, *in* Reynolds, R.E., ed., Wild, scenic and rapid, a trip down the Colorado River trough, Field trip guide and abstracts from the 2007 Desert Symposium: Northridge, California State University, and LSA Associates, p. 5–32.

Roskowski, J.A., Patchett, P.J., Spencer, J.E., Pearthree, 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.

Sarna-Wojcicki, A.M., Lajoie, K.R., Meyer, C.E., Adam, D.P., and Rieck, H.J., 1991, Tephrochronologic correlation of upper Neogene sediments along the Pacific margin, conterminous United States, *in* Morrison, R.B., ed., Quaternary nonglacial geology; Conterminous U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. K-2, p. 117–140.

Sarna-Wojcicki, A.M., Deino, A.L., Fleck, R.J., McLaughlin, R.J., Wagner, D., Wan, E., Wahl, D., Hillhouse, J.W., and Perkins, M.E., 2011, Age, composition and areal distribution of the Pliocene Lawlor Tuff, and three younger Pliocene tuffs, California and Nevada: Geosphere, v. 7, p. 599–628, doi:10.1130/GES00609.1.

Smith, P.B., 1970, New evidence for a Pliocene marine embayment along the lower Colorado River area, California and Arizona: Geological Society of America Bulletin, v. 81, p. 1411–1420, doi:10.1130/0016-7606(1970)81[1411:NEFAPM]2.0.CO;2.

Spencer, J.E., and Patchett, P.J., 1997, Sr isotope evidence for a lacustrine origin for the upper Miocene to Pliocene Bouse Formation, lower Colorado River trough, and implications for timing of Colorado Plateau uplift: Geological Society of America Bulletin, v. 109, p. 767–778, doi:10.1130/0016-7606(1997)109<0767:SIEFAL>2.3.CO;2.

Spencer, J.E., Ferguson, C.A., Pearthree, P.A., and Richard, S.M., 2007, Geologic map of the Boundary Cone 7.5′ quadrangle, Mohave County, Arizona, v 1.0: Arizona Geological Survey Digital Geologic Map DGM-54, 23 p., scale 1:24,000.

Spencer, J.E., Pearthree, P.A., and House, P.K., 2008, 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 biotic perspectives: Geological Society of America Special Paper 439,.p. 375–390, doi:10.1130/2008.2439(17).

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

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.

U.S. Bureau of Reclamation, 2012, Colorado River basin water supply and demand study: Study report: U.S. Department of the Interior Bureau of Reclamation, 85 p., http://www.usbr.gov/lc/region/programs/crbstudy/finalreport/studyrpt.html.