

River-evolution and tectonic implications of a major Pliocene aggradation on the lower Colorado River: The Bullhead Alluvium

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ABSTRACT

The ~200-m-thick riverlaid Bullhead Alluvium along the lower Colorado River downstream of Grand Canyon records massive early Pliocene sediment aggradation following the integration of the upper and lower Colorado River basins. The distribution and extent of the aggraded sediments record (1) evolving longitudinal profiles of the river valley with implications for changing positions of the river's mouth and delta; (2) a pulse of rapid early drainage-basin erosion and sediment supply; and (3) constraints on regional and local deformation.

The Bullhead Alluvium is inset into the Hualapai and Bouse Formations along a basal erosional unconformity. Its base defines a longitudinal profile interpreted as the incised end result after the Colorado River integrated through lake basins. Subsequent Bullhead aggradation, at ca. 4.5–3.5 Ma, built up braid plains as wide as 50 km as it raised the Colorado River's grade. We interpret the aggradation to record a spike in sediment supply when river integration and base-level fall destabilized and eroded relict landscapes and Tertiary bedrock in the Colorado River's huge catchment.

Longitudinal profiles of the Bullhead Alluvium suggest ≥ 200 m post-Bullhead relative fault uplifts in the upper Lake Mead area, >100 m local subsidence in the Blythe Basin, and deeper subsidence of correlative deltaic sequences in the Salton Trough along the Pacific–North American plate boundary. However, regionally, for >500 km along the river corridor from Yuma, Arizona, to Lake Mead, Arizona and Nevada, the top of the Bullhead Alluvium appears to be neither uplifted nor tilted, sloping 0.5–0.6 m/km downstream like the gradient of a smaller late

Pleistocene aggradation sequence. Perched outcrops tentatively assigned to the Bullhead Alluvium near the San Andreas fault system project toward a Pliocene seashore or bay-line twice as distant (300–450 km) as either the modern river's mouth or a tectonically restored 4.25 Ma paleoshore. We conclude that Bullhead aggradation peaked after 4.25 Ma, having lengthened the delta plain seaward by outpacing both 2 mm/yr delta subsidence and 43–45 mm/yr transform-fault offset of the delta. Post-Bullhead degradation started before 3.3 Ma and implies that the river profile lowered and shortened because sediment supply declined, and progradation was unable to keep up with subsidence and plate motion in the delta.

INTRODUCTION

The Colorado River in southwestern North America drains from the Rocky Mountains through the Colorado Plateau and Grand Canyon to the Basin and Range Province and the Gulf of California (Fig. 1). About 5–6 Ma, the river left an uncertain prior path and coursed from Grand Canyon through the Basin and Range Province toward the opening Gulf of California. The new path through the Basin and Range Province resulted in a series of overspilling river-fed lakes, into which the Bouse Formation was deposited (Spencer and Patchett, 1997; House et al., 2008b; Spencer et al., 2013; Pearthree and House, 2014; Crossey et al., 2015). Water and sediment ultimately entered subsiding basins in the Salton Trough and the opening Gulf of California along the transtensional North America–Pacific plate boundary. Karlstrom et al. (2007, 2008) calculated incision rates and used them and other data on the river's 5 m.y. evolution in Grand Canyon and in the lower Colorado River corridor to evaluate and model uplift of the Colorado Plateau.

A thick sequence of Pliocene fluvial Colorado River sediments herein named the Bullhead Alluvium is deeply inset into the eroded Bouse Formation along the river's corridor in the Basin and Range Province (Fig. 2). The inset records an incised river that presumably evolved from spillover of lakes, erosion of their paleodams, disgorging of sediment fill successively into lower basins, and eventual establishment of a new river grade to the sea (House et al., 2005, 2008b; Spencer et al., 2008, 2013; Pearthree and House, 2014; Crossey et al., 2015). The Bullhead Alluvium and proposed correlatives record a subsequent extraordinary fluvial aggradation pulse that temporarily raised the grade along the lower Colorado River 200–300 m (Pearthree and House, 2014). This pulse was bigger than several younger aggradation-degradation cycles affecting the lower Colorado River.

The goal of this paper is to examine the geometry, timing, and alternate geomorphic and tectonic explanations for this exceptional aggradation of a continental-scale Colorado River system. We characterize and name the Bullhead Alluvium and correlate it with other alluvial units along the lower Colorado River corridor from near the mouth of the Grand Canyon to the Salton Trough. Data from drilling for water, petroleum, and engineering studies complement observations of exposed outcrops and provide key stratigraphic and paleontological information. We make use of some drill-hole information not widely available (Berkey, 1935a, 1935b; USBR, 1935; Woodward-McNeill & Associates, 1975; Winterer, 1975; Fugro, 1976; Lee and Bell, 1976; Fritts, 1976; Kukla and Updike, 1976). We use the distribution of previously known and newly discovered occurrences of Pliocene fluvial deposits to analyze the river's evolving longitudinal profile from the time before to after the Bullhead aggradation (Fig. 3). For base level for the river imposed by sea level



Fig. 1

Figure 1. Map of Colorado River drainage basin (green) in the southwestern United States and its relation to plate-boundary faults of the San Andreas fault (SAF) system and the diffuse Eastern California shear zone (ECSZ). LS—Laguna Salada; SW—Sacramento Wash. Text explains restoration of the positions of Fish Creek–Vallecito and Altar Basins.

in the Gulf of California, we assume Pliocene sea levels of 22 ± 15 m higher than modern sea level (Raymo et al., 2009; Miller et al., 2012; Spencer et al., 2013; cf. Raymo and Mitrovica, 2012; Fig. 3B). We relate the evolving river profile to changing positions of the bayline—the junction of the upward-sloping alluvial profile with the coastal plain, at or near sea level (see Shanley and McCabe, 1994). Our analysis of the aggradation suggests that the river profile's rise and fall in relation to its delta's seashore or bayline in the Salton Trough have implications for evolution of the Bouse Formation, the Colo-

rado River, Grand Canyon, sediment supply from the Colorado River drainage basin, and regional and local tectonics.

GEOLOGIC FRAMEWORK OF PRE-BULLHEAD COLORADO RIVER SEDIMENTS

Sediments delivered by the Colorado River from the Colorado Plateau appear abruptly sometime between 6.0 and 4.4 Ma in the stratigraphic record of the Basin and Range Province west of the mouth of the Grand Canyon, overlying the

Hualapai Limestone and other interior basin deposits (Spencer et al., 2001; Faulds et al., 2001). Table 1 summarizes timing constraints on the Pliocene evolution of the lower Colorado River. River-derived sediments first appear in Cottonwood Valley after 5.6 Ma (House et al., 2008b). They appear in the marine stratigraphic record in the Salton Trough at a horizon correlated to 5.3 Ma, followed by a sediment-starved interval before sustained accumulation of large amounts beginning only after 4.9 Ma (Dorsey et al., 2007, 2011). Detritus delivered by the Colorado River includes Colorado Plateau–derived detrital zircons, detrital Cretaceous microfossils, moderately sorted subrounded sand, hematite-coated quartz grains with syntaxial overgrowths, and (in fluvial deposits) well-rounded nonlocal pebbles and cobbles of chert, quartzite, and fossiliferous Paleozoic limestone (Merriam and Bandy, 1965; Lucchitta, 1972; Winker, 1987; Busing, 1990; Fleming, 1994; Dorsey et al., 2007, 2011; Kimbrough et al., 2011, 2015).

The downstream integration of the river from Grand Canyon through a succession of filling-and-spilling events in the river corridor is recorded in proximal delta-plain deposits that conformably overlie the Miocene Hualapai Limestone in Greggs Basin (Fig. 4) and in lacustrine and deltaic Bouse Formation sediments that accumulated in a series of basins downstream (Howard and Bohannon, 2001; Spencer and Patchett, 1997; House et al., 2008b; Pearthree and House, 2014; Appendix Table A1). Much of the Bouse Formation consists of sediments delivered by the Colorado River (Busing, 1990; Kimbrough et al., 2015). Upward transitions in the Bouse Formation from limestone to claystone to fluvial deposits record transitions from carbonate deposition in clear-water lakes to voluminous deltaic deposition and basin filling, leading to spillover of sediment into successive basins (Fig. 5; Busing, 1990; Pearthree and House, 2014). River incision began before 4.7 Ma in Greggs Basin (Howard et al., 2000), and before 4.9–4.6 Ma in Detrital Valley and near Hoover Dam (Felger et al., 2011). Incision progressed downstream (Spencer et al., 2013). Incision in the Blythe Basin postdates deposition there of Bouse Formation lacustrine limestone and the interbedded ca. 4.83 Ma Lawlor Tuff, which crop out at elevations ~ 300 m above sea level (masl; Spencer et al., 2013; Harvey, 2014; Miller et al., 2014; Table 1). A small amount of Colorado River sediment somehow reached the Salton Trough 5.3–5.2 Ma, but substantial Colorado River sedimentation there began only after 4.8 Ma (Dorsey et al., 2011).

Subsiding basins in the Salton Trough along and near the San Andreas fault captured the sediments delivered by the Colorado River and

Figure 2. Map of lower Colorado River corridor. Approximate original extent of Pliocene river deposits is estimated from their extent in the Salton Trough and river corridor and from projecting the elevations of highest preserved outcrops across the modern river corridor's topography based on its resemblance to the sub-Bullhead valley shapes. The Altar-Algodones fault is considered a southeastern extension of the San Andreas fault. C Flt.—Callville fault; W Flt.—Wheeler fault. Some faults are not shown.

record timing, sediment character, and evolving delta geometry, which are key to interpreting the river's early evolution (Figs. 6 and 7; Appendix 3). The best-dated record is a thick, well-documented section exposed in the Fish Creek–Vallecito Basin (Winker and Kidwell, 1986, 1996; Dorsey et al., 2007, 2011; Figs. 1 and 7). Detailed paleomagnetic correlations of the units there (e.g., Fig. 6; Table 1) are constrained by the biostratigraphic Miocene-Pliocene boundary and by two U-Pb–dated tuffs in the late Pliocene part of the section. The marine Imperial Group there includes the oldest Colorado River–derived sand—turbidite sandstone near the biostratigraphic Miocene-Pliocene boundary and magnetostratigraphically closely correlated to 5.3 Ma (Dorsey et al., 2007, 2011). An overlying marine claystone (ca. 5.1–4.9 Ma) is in turn overlain by ~900 m of Colorado River–derived deposits that record progradation of the Colorado River delta, evolving from offshore marine prodelta to delta-platform to marginal-marine delta-front environments. Pliocene fluvial deposits of the Arroyo Diablo Formation (of the Palm Spring Group) overlie the marine strata at a horizon correlated to ca. 4.25 Ma and mark the prograding arrival of the Colorado River fluvial delta plain in the Fish Creek–Vallecito Basin (Figs. 6 and 7). Its position therefore establishes the 4.25-Ma bayline.

Closer to the head of the modern river's fluvial delta near Yuma, Arizona, the Fortuna and San Luis Basins lie on either side of the Algodones fault (Fig. 2). Drill logs in both basins contain a subsurface record of transition from estuarine to fluvial deltaic conditions as the Colorado River's delta prograded: Subsurface estuarine deposits (correlated to the Bouse Formation by Olmsted et al., 1973) are capped by a deltaic transition zone of fluvial sand and gravel interbedded with fossiliferous estuarine clay and silt. The transition zone is 25–76 m thick in the Fortuna Basin and up to 770 m thick in the San Luis Basin (Olmsted et al., 1973; Mattick

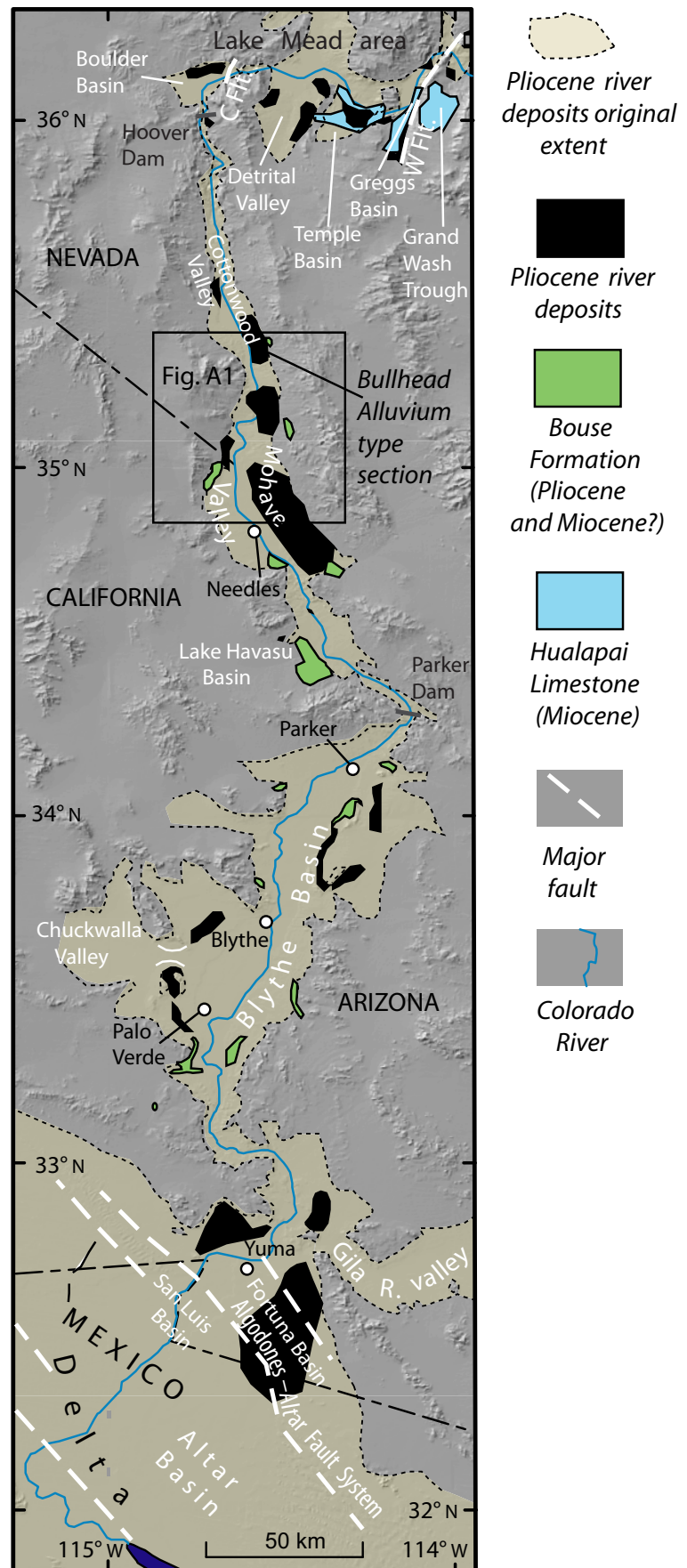
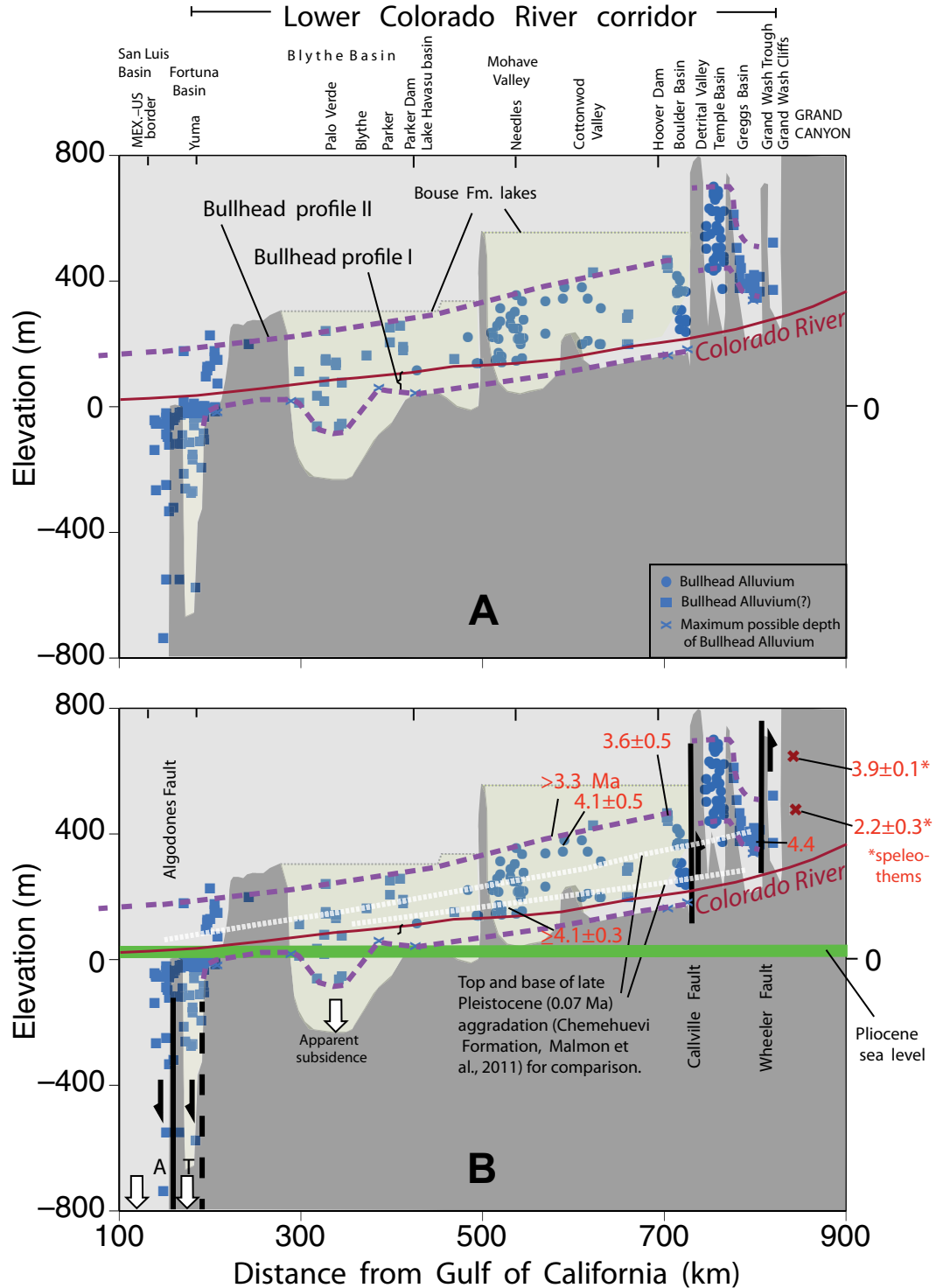


Figure 3. Longitudinal profile of elevations of exposed Pliocene Bullhead Alluvium (dots) and tentatively identified exposed and subsurface Bullhead Alluvium (squares) projected to the historic Colorado River (red curve from La Rue, 1925). Bedrock canyons are shown in gray. Pre-Bullhead Bouse Formation lakes are from Spencer et al. (2013). Dated pre-Bullhead units (Table 1) restrict the Bullhead strata to be younger than 6.0 Ma Hualapai Limestone in Temple Basin, younger than 5.6 Ma Lost Cabin beds that underlie Bouse Formation in Cottonwood Valley, and younger than 4.8 Ma Bouse Formation in Blythe Basin. (A) Bullhead profile II is the estimated top of the Bullhead Alluvium. Bullhead profile I at the base of the aggradation sequence is bracketed between the lowest exposures (typically near modern river level) and uncertainly correlated subsurface occurrences (see Table A1). Pre-Bullhead Bouse Formation, Miocene rocks, or basement below undated Colorado River deposits at dam sites and other locales in the valley that limit the maximum possible depths of Bullhead strata (blue Xs). (B) Dates (red, in Ma) in the Bullhead strata are from Faults et al. (2001), House et al. (2008b), and Matmon et al. (2012); dated speleothems are from Polyak et al. (2008; elevations from Polyak, 2013, written commun.). Envelopes on the elevation extent of the late Pleistocene Chemehuevi Formation (0.07 Ma; Malmon et al., 2011) are shown for comparison with the Bullhead profiles.



et al., 1973; Eberly and Stanley, 1978). Marine $^{87}\text{Sr}/^{86}\text{Sr}$ isotopic ratios measured by Spencer and Patchett (1997) on mollusk shells from the transition zone, 211 and 248 m above its base in the San Luis Basin (Eberly and Stanley, 1978), establish a marine environment for the Colorado River's delta near the southern Arizona-Mexico border. The transition zone and undated allu-

vium that overlies it are subsided deep below modern and Pliocene sea levels (Fig. 7; Olmsted et al., 1973; Eberly and Stanley, 1978).

Test wells in the subsided Altar Basin to the south similarly document upward transitions from open-marine to deltaic marine and then to fluvial facies (Figs. 6 and 7; Pacheco et al., 2006). Marine "sequence B" of Pacheco et al.

(2006) in the Altar Basin is typically ~2 km thick and downlaps southward in seismic images onto deeper marine sediments, which led Pacheco et al. (2006) to interpret their sequence B as a Colorado River-derived prodelta sequence (Fig. 6). It is overlain by fluvial sediments. A seismic image (Pacheco et al., 2006) reveals continuity of a long section in the Altar Basin

TABLE 1. TIMING CONSTRAINTS ON THE EARLY HISTORY OF THE LOWER COLORADO RIVER

Estimated age (Ma)	Event	Datum	Reference
5.97 ± 0.07	Continued deposition of Hualapai Limestone (dated ~50 m below the formation's top) predates arrival of Colorado River sediments into the Basin and Range from Grand Canyon.	Dated tephra.	Spencer et al. (2001).
5.59 ± 0.05	Deposition of Lost Cabin beds in Cottonwood Valley. Predates arrival of Colorado River water and deposition of Bouse Formation in this basin.	Tephra correlation. (A possible correlation to a tuff dated 5.84 Ma [Anders et al., 2009; Spencer et al., 2013] is considered unlikely [Kathryn Watts, 2013, written commun.]).	House et al. (2008b).
≥5.3, ≤8.1	Lower parts of Bouse Formation deposited in the Blythe Basin below about 110 m above sea level (masl).	Foraminifers.	McDougall and Martinez (2014).
5.35 ± 1.65/–0.97	Deposits of Hualapai Wash: Colorado River sediment interpreted as delta-plain facies spread over an undissected floor of Hualapai Limestone in Gregg's Basin area.	Tentative cosmogenic burial date (2-point profile).	Matmon et al. (2012).
5.33 (or 5.3 ± 0.1)	First arrival of Colorado River–derived C-suite sediment in the Fish Creek–Vallecito Basin (Wind Caves Member of the marine Latrania Formation).	Magnetostratigraphy and biostratigraphy. Two dated late Pliocene tuffs also constrain magnetostratigraphic correlations of entire Pliocene section in this basin.	Dorsey et al. (2007).
ca. 5.1 to 4.9	Sediment-starved claystone interval in Fish Creek–Vallecito Basin implies interruption of Colorado River sediment supply.	Magnetostratigraphy of marine claystone.	Dorsey et al. (2007, 2011).
4.83 Ma	Bouse Formation basin-margin limestone at 306 masl in Blythe Basin shows that the basin was inundated to this high level, likely in a lake.	Tephra correlation.	Spencer et al. (2013), Harvey (2014), Miller et al. (2014).
ca. 4.8	New influx of Colorado River–derived sediment reached the Fish Creek–Vallecito basin.	Magnetostratigraphy.	Dorsey et al. (2011).
4.71 ± 0.03	Fluvial incision had begun into the Hualapai Limestone and its correlatives in Gregg's Basin.	Dated basalt interbedded with ancestral Grand Wash tributary gravels, projecting toward a position inset into Hualapai Limestone.	Howard and Bohannon (2001), Howard et al. (2010).
By 4.6	Detrital Cretaceous foraminifera derived from the Mancos Shale deposited in Fish Creek–Vallecito basin. Their common occurrence in Colorado River alluvium above the Bouse Formation in Blythe Basin is undated.	Magnetocorrelation of lowest horizon of detrital Cretaceous forams in Fish Creek section.	Merriam and Bandy (1965), Fritts (1976), Dorsey et al.'s data repository (2007).
After 5.6, before 4.1 ± 0.5	Bouse Formation that had accumulated in standing water in Mohave and Cottonwood Valleys was deeply incised as Colorado River established its Bullhead profile I.	Tephra correlations.	House et al. (2008b).
ca. 4.5	Rate of tectonic subsidence doubled or tripled in the Fish Creek–Vallecito Basin, even while Colorado River–derived sediment built up the marine delta to shallow depths.	Magnetostratigraphy.	Dorsey et al. (2011).
4.41 ± 0.03	Basalt flowed onto river gravel in Gregg's Basin during accumulation of gravel-sand aggradational section ≥60 m thick.	Dated basalt interbedded in Colorado River conglomerate. Age supported by cosmogenic burial age ≥4.8 ± 1.0/–0.7 Ma on underlying fluvial gravel.	Faulds et al. (2001), Howard et al. (2008), Matmon et al. (2012).
ca. 4.25	Fluvial sediments (Arroyo Diablo Formation) of the Colorado River arrive in the Fish Creek–Vallecito Basin.	Magnetostratigraphy.	Dorsey et al. (2011).
≥4.1 ± 0.3	Fluvial aggradation of Bullhead Alluvium in progress (at least 20 m thick) in southern Mohave Valley.	Cosmogenic burial age.	Matmon et al. (2012).
4.1 ± 0.5	Bullhead Alluvium aggradation reached within 10 m of its highest preserved elevation (250 m above lowest elevations) in northern Mohave Valley.	Tephra correlation.	House et al. (2008b).
3.6 ± 0.5	High-level Colorado River gravels filled a sculpted bedrock channel and a paleovalley near Hoover Dam, at a level near the projected top of the Bullhead Alluvium.	Cosmogenic burial-age profile combined with a buried clast in a nearby section.	Matmon et al. (2012).
3.29 ± 0.05 (3.3)	Post–Bullhead Alluvium degradation by fluvial incision was at least 50 m below top of Bullhead Alluvium in northern Mohave Valley.	Tephra correlation of Nomlaki Tuff within an inset alluvial fan.	House et al. (2005, 2008b).
2.2 and younger	Post–Bullhead Alluvium piedmont fan deposition continued over eroded Bullhead Alluvium in Mohave Valley.	Cosmogenic exposure ages of fan gravels.	Fenton and Pelletier (2013).

that lacks obvious unconformities, even though faults complexly segment nearby parts of the basin (González-Escobar et al., 2009; Martín-Barajas et al., 2013).

Reconstructing the Colorado River's deltaic evolution requires restoring the basins for dextral fault offsets along the plate boundary. The San Luis, Altar, Fish Creek–Vallecito, and Laguna Salada Basins in the Salton Trough restore to the southeast in the Pliocene relative to Yuma and the

lower Colorado River corridor. The Fish Creek–Vallecito Basin has been tectonically offset an estimated 181–191 km since 4.25 Ma, assuming the San Andreas fault system, including the Algodones–Altar fault(s), has accommodated 43–45 mm/yr northwestward relative translation (80%–85% of the 50 mm/yr of the Pacific plate motion; e.g., Bennett et al., 1996; Plattner et al., 2007). Alternatively, restoring at a rate of 275–300 km translation since 6 Ma (Oskin and

Stock, 2003) yields 194–212 km of offset of Fish Creek since 4.25 Ma. Figure 1 restores Fish Creek 190 km at 4.25 Ma and restores the Altar Basin 155 km at 3.5 Ma.

BULLHEAD ALLUVIUM

The “Bullhead alluvium,” originally described from Cottonwood and Mohave Valleys, can be extended to correlative deposits along most

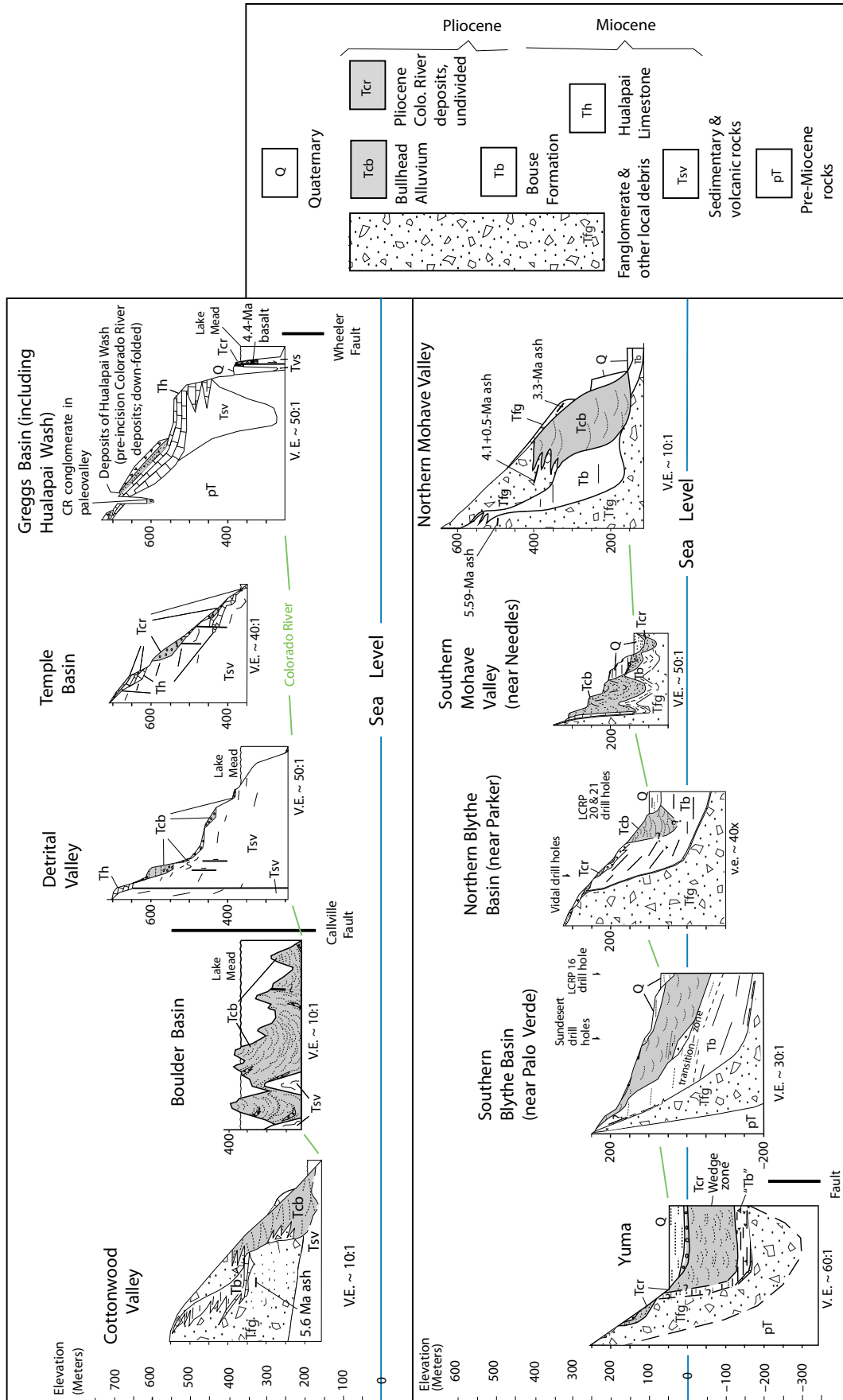


Figure 4. Simplified stratigraphy of Pliocene Colorado River (CR) deposits. Sections are arranged upstream to downstream from upper right to lower left. Approximate vertical exaggerations (V.E.) vary between sections. Boulder Basin section is after Longwell (1936). Yuma area includes Bard Valley. Table A1 contains notes and references.

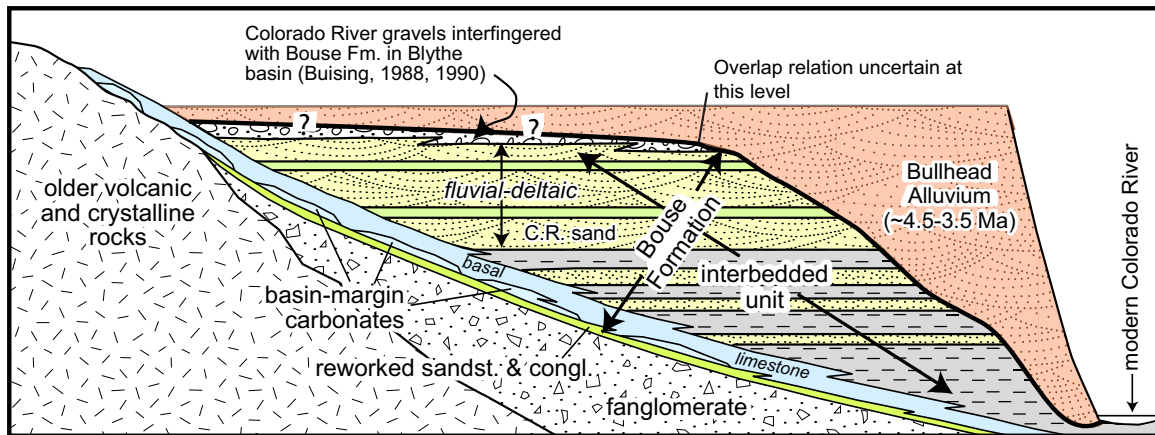


Figure 5. Conceptual stratigraphic architecture of the Bouse Formation (modified from Buising, 1990) in relation to the Bullhead Alluvium. Locally derived gravels (not shown) form interbeds in the Bouse and Bullhead units. Elevation difference between the lowest and highest exposures of the Bullhead Alluvium typically exceeds 200 m. Relations between the Bullhead and uppermost Bouse Formations and between the Bouse Formation interbedded unit and basin-margin carbonates are subjects of ongoing research. C.R.—Colorado River.

of the lower Colorado River corridor. These deposits together define a substantial episode of Pliocene valley aggradation soon after full connection of the Colorado River to the Gulf of California. We define and characterize this unit here as the Bullhead Alluvium, discuss correlations to sections all along the lower Colorado River corridor and in the Salton Trough, and explore its key role in the early evolution of the Colorado River.

Name and Lithologic Character

House et al. (2005, 2008b) and Pearthree and House (2014) described a thick sequence of moderately consolidated to cemented Pliocene Colorado River sediments in Cottonwood and Mohave Valleys that they informally called alluvium of Bullhead City or Bullhead alluvium. Locally, it contains a Pliocene tephra bed (House et al., 2005, 2008b). We propose to designate this unit as a mappable formation, the Bullhead Alluvium (Appendix 1). A combination of lithologic characteristics and stratigraphic position defines the Bullhead Alluvium as a lithostratigraphic formation along the corridor of the lower Colorado River. The formation is inset unconformably into the underlying Bouse Formation. The Bullhead Alluvium exhibits cut-and-fill structures, trough cross-bedding, well-sorted sandstone and clast-supported conglomerate, and a suite of detrital types indicative of deposition by the Colorado River and its tributaries (Fig. 8; Appendix 1). Petrified wood is common. Appendix 1 describes proposed stratotype and reference sections and describes the formation in its various basins and proposed correlative sections in other basins.

The Bullhead Alluvium plays a key role in a growing body of evidence documenting the establishment and early history of Colorado River. Deposits of the Bullhead Alluvium were included in “unit B of older alluviums” by Metzger and Loeltz (1973) and Metzger et al. (1973). Our subsequent work has shown that unconformities that bound the base and top of the Bullhead Alluvium define it as the largest depositional sequence within unit B. The distribution of the unconformable basal contact below remnants of the Bullhead Alluvium defines a paleovalley shape roughly coincident with the modern Colorado River valleys. We distinguish the inset Bullhead Alluvium conceptually from lithologically very similar Colorado River sandstone and conglomerate beds that Buising (1990) reported as interbedded with the upper part of the underlying Bouse Formation (Fig. 5).

The Bullhead Alluvium was first recognized in Cottonwood and Mohave Valleys, where we assign a stratotype in the Tyro Wash area, Arizona, and a reference section near Laughlin, Nevada (Fig. 8G; Appendix 1). The Tyro Wash stratotype section consists of 205 m of exposed sandstone and conglomerate with neither the lowest base nor top of the formation continuously exposed (Appendix Fig. A1; see also Pearthree and House, 2014). The Laughlin reference section (Appendix Fig. A1B) exposes the erosional base of the Bullhead Formation on older Bouse Formation and sub-Bouse deposits (see also House et al., 2005, 2008b; Pearthree and House, 2014). High exposures of the Bullhead Alluvium on the nearby piedmont east across the river, which include locally derived alluvial-fan interbeds, reach 233 m higher in elevation, indicating the formation is at least this thick (Fig. A1B).

Regional Extent

We correlate the Bullhead Alluvium to sandstone-conglomerate sections inset in Boulder and Lake Havasu Basins, Detrital Wash, and part of the Blythe Basin (Figs. 2, 3, 4, and 6; Appendix 2; Table A1). Similar deposits even farther upstream and downstream extend the longitudinal record from upper Lake Mead downstream to Yuma and the Algodones fault. These latter deposits have elevation ranges, geomorphic position, and lithologic character that suggest probable but less certain correlation to the Bullhead Alluvium (Figs. 5 and 6; Appendix 2). In the Lake Mead area, these sections include fragmentary cemented deposits in the Grand Wash Trough, an aggradation sequence >60 m thick in Gregg's Basin containing the interbedded basalt of Sandy Point, sections in Temple Basin, and 28 m of Colorado River sediments perched above Hoover Dam. Some older deposits stranded during stages of the pre-Bullhead incision possibly are inadvertently included. Local angular unconformities record syndepositional warping and folding (wavelengths <1 km) within the Bullhead Alluvium in Boulder Basin and southern Mohave Valley (Longwell, 1936; Metzger and Loeltz, 1973; Howard et al., 2013; Fig. 4).

Erosional inset relations in the Blythe Basin (Metzger et al., 1973) and our reconnaissance lead to the inference that most of the exposed and subsurface unit B of Metzger et al. (1973) and the equivalent unit QTrb of Fugro (1976) there correlate to the Bullhead Alluvium. Further field study in that basin still is required to fully separate pre-Bullhead fluviodeltaic Colorado River deposits, which are interbedded

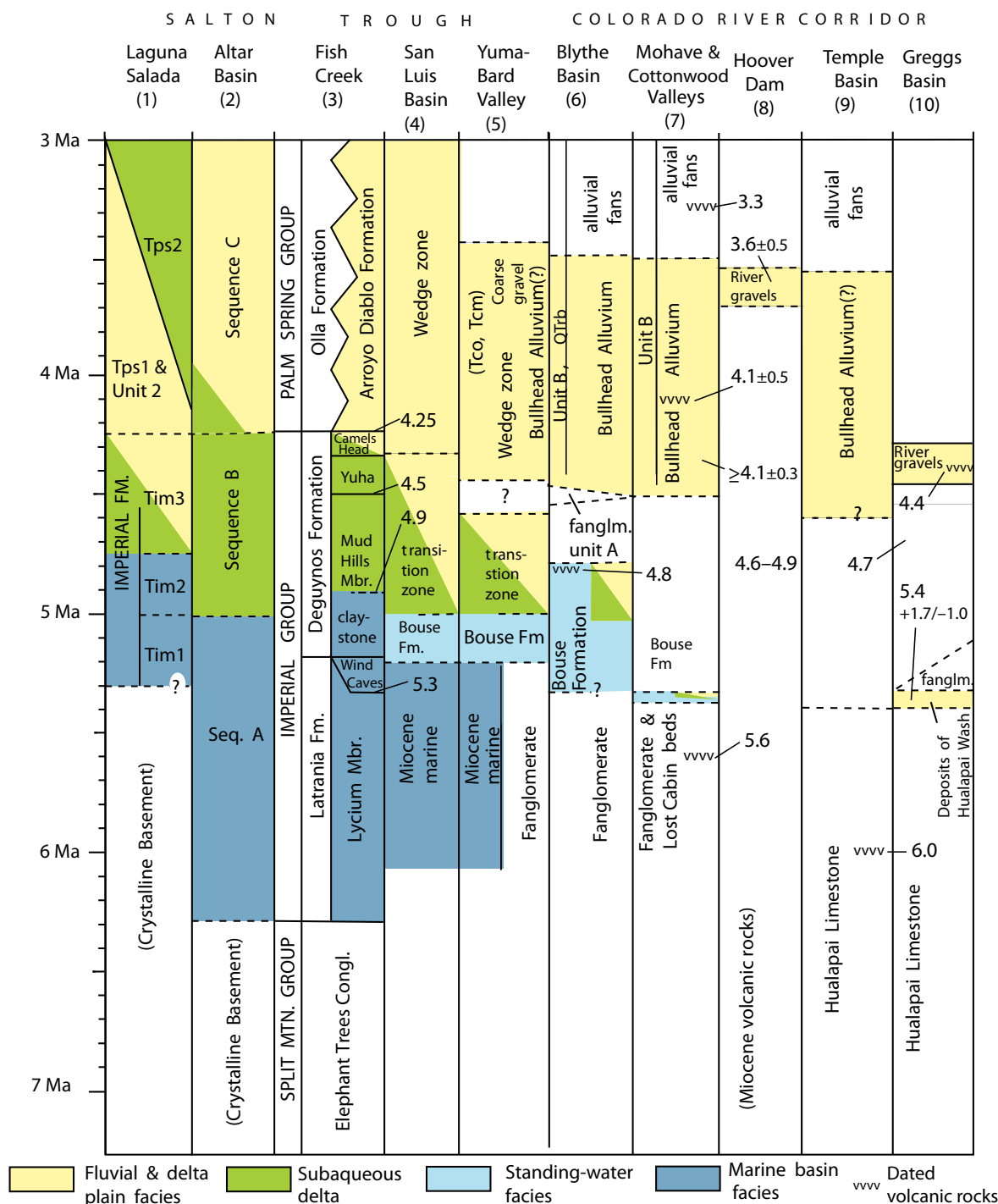


Figure 6. Proposed correlation of sections, arranged from upstream (right) to downstream (left). Sources: (1) Dorsey and Martín-Barajas (1999), Martín-Barajas et al. (2001); (2) Pacheco et al. (2006); (3) Dorsey et al. (2011), stratigraphic names largely from Winker and Kidwell (1996); (4) Olmsted et al. (1973), Eberly and Stanley (1978); (5) Olmsted et al. (1973); (6) Metzger et al. (1973), Lee and Bell (1976), Fritts (1976), Buising (1990); (7) Metzger and Loeltz (1973), House et al. (2005, 2008b); (8) Matmon et al. (2012); (9) Spencer et al. (2001), this report; (10) Faulds et al. (2001, 2008), Matmon et al. (2012). Correlation dates (in Ma) in the Fish Creek–Vallecito Basin (column 3), based on detailed paleomagnetic correlations (mostly well within ± 0.1 m.y., constrained by biostratigraphy low in the section and dated tuffs high in the section), date the 5.3 Ma base of the Wind Caves Member (of the Latrania Formation; lowest Colorado River–derived sand) and the 4.25 Ma base of the Arroyo Diablo Formation (dominantly Colorado River alluvium) and Olla Formation (locally derived alluvium). Dates (Ma) in other columns are referenced in Table 1.

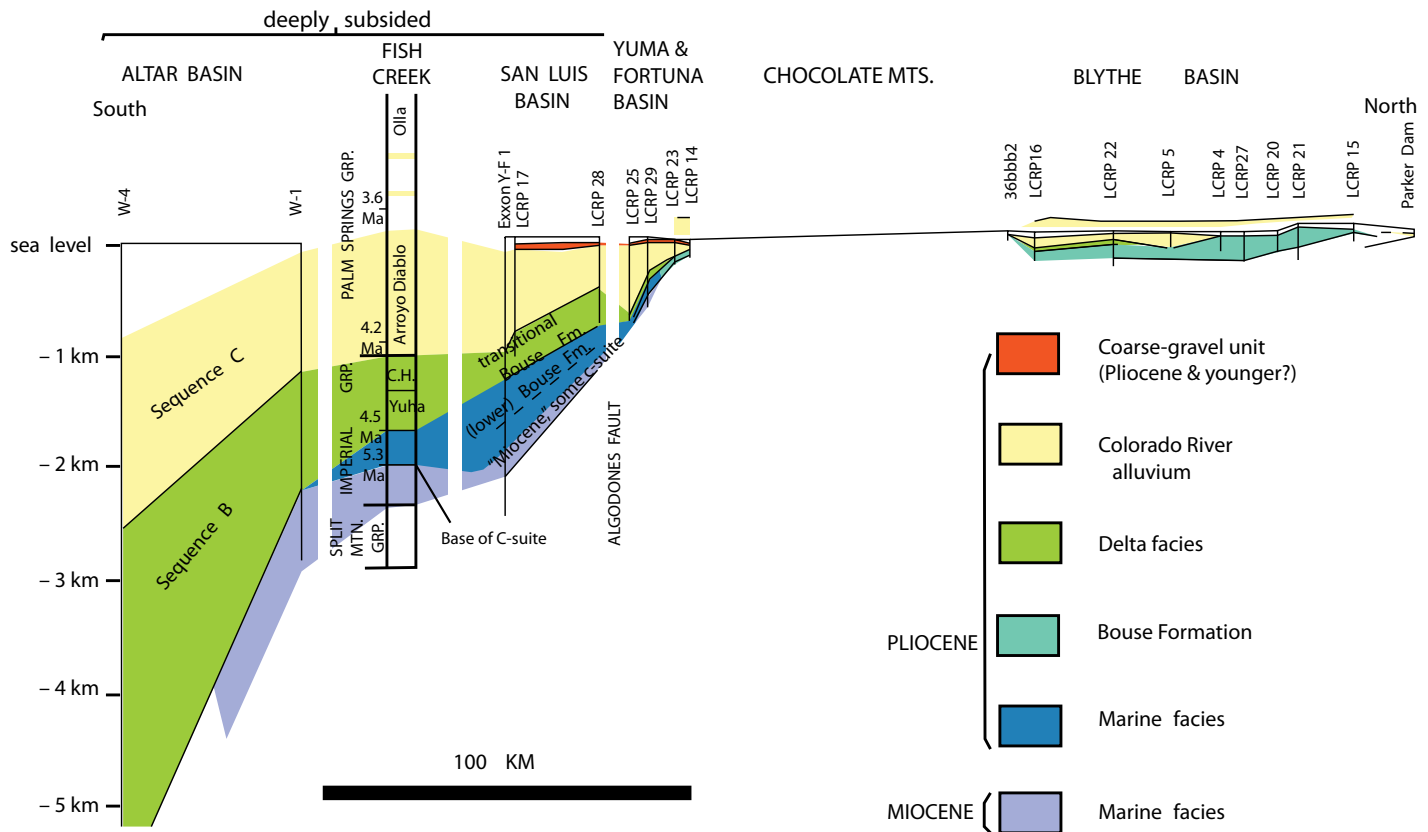


Figure 7. Thickness and facies of measured stratigraphic sections in the lower Colorado River corridor and the Colorado River delta area. For comparing thicknesses, the displaced Fish Creek section (Dorsey et al., 2011) is placed between Altar and San Luis Basins. Sources for identified wells: Pacheco et al. (2006, Altar Basin); Eberly and Stanley (1978, San Luis Basin), Olmsted et al. (1973, San Luis and Fortuna Basins and Yuma), Metzger et al. (1973, Blythe Basin). Thicknesses of the Fish Creek–Vallecito and inferred correlative Pliocene stratal packages (see Fig. 6) indicate abrupt thickening of Colorado River–derived deposits from Blythe Basin to near and across the Algodones fault of the San Andreas fault system (leftward in the diagram). Colorado River alluvium is subsided deeply below sea level in the Altar and San Luis Basins in the Salton Trough. Delta facies shown include prodelta beds in the Altar Basin, nearshore marine deltaic beds in the Fish Creek–Vallecito Basin, and interbedded nearshore and alluvial beds in the San Luis and Fortuna Basins and Yuma area; Colorado River alluvial deposits overlying them are inferred to record progradation of the delta. Delta facies shown in the Blythe Basin were described as transition zone “fluvial Bouse” containing both indigenous and reworked Bouse Formation fauna (Fritts, 1976).

with the top of the underlying Bouse Formation (Fig. 5). In the subsurface, Metzger et al.’s (1973) identification of unit B and its contact on underlying Bouse Formation cannot be retested without new drilling, but it is supported by several factors. Bouse Formation foraminifera were reported up to the contact but not above it (Smith, 1970; McDougall, 2011). A transition zone, ~30 m thick, forming the upper part of the subsurface Bouse Formation near sea level in the Palo Verde area (Figs. 3 and 4), contains both indigenous Bouse Formation foraminifera and reworked equivalent fauna, in contrast to the overlying fluvial unit QTrb, in which the only foraminifera observed are detrital Cretaceous ones (Fritts, 1976). A locally derived subsurface angular alluvial-fan conglomerate between the Bouse Formation and overlying QTrb unit (Fugro, 1976) supports the idea that an uncon-

formity bounds the base of QTrb, much like a similar relation at the base of the Bullhead Alluvium in Chemehuevi, Mohave, and Cottonwood Valleys. In Figure 4, we project the transition zone downdip basinward and correlate it tentatively with a sand-rich upper part of the Bouse Formation logged in test well LCRP-16 by Metzger et al. (1973).

Exposed older Colorado River alluvial deposits in the Yuma area (Fig. 4) also closely resemble Bullhead Alluvium in lithology, structure, large thickness, presence of fossil wood, and elevation of the highest exposed deposits along the downstream projection of the Bullhead Alluvium (Fig. 3). Nations et al. (2009) described clast content, sedimentary structures, and paleocurrent directions. Petrified wood there includes California bay laurel, palm, walnut, cottonwood, and conifer (Nations et al., 2009). According to

Olmsted et al. (1973), the exposed older Colorado River alluvial deposits at Yuma represents a complex of aggradation fills separated by degradational scouring, although it seems possible that fluvial channeling may account for some of the erosional breaks.

The Bullhead Alluvium and its probable correlatives are gravel-rich in Greggs Basin and generally fine downstream to coarse to medium sandstone with subordinate conspicuous roundstone conglomerate intervals and local mudstone from Detrital Valley to Yuma (Fig. 8; Appendices 1 and 2). Boulder beds occur at or near the base of the unit in Greggs and Temple Basins and Cottonwood and Mohave Valleys (Fig. 8F), and there is an interbed of locally derived coarse limestone and basalt blocks in Detrital Valley (Appendix Table A1). Locally derived gravels and sands interfinger with the

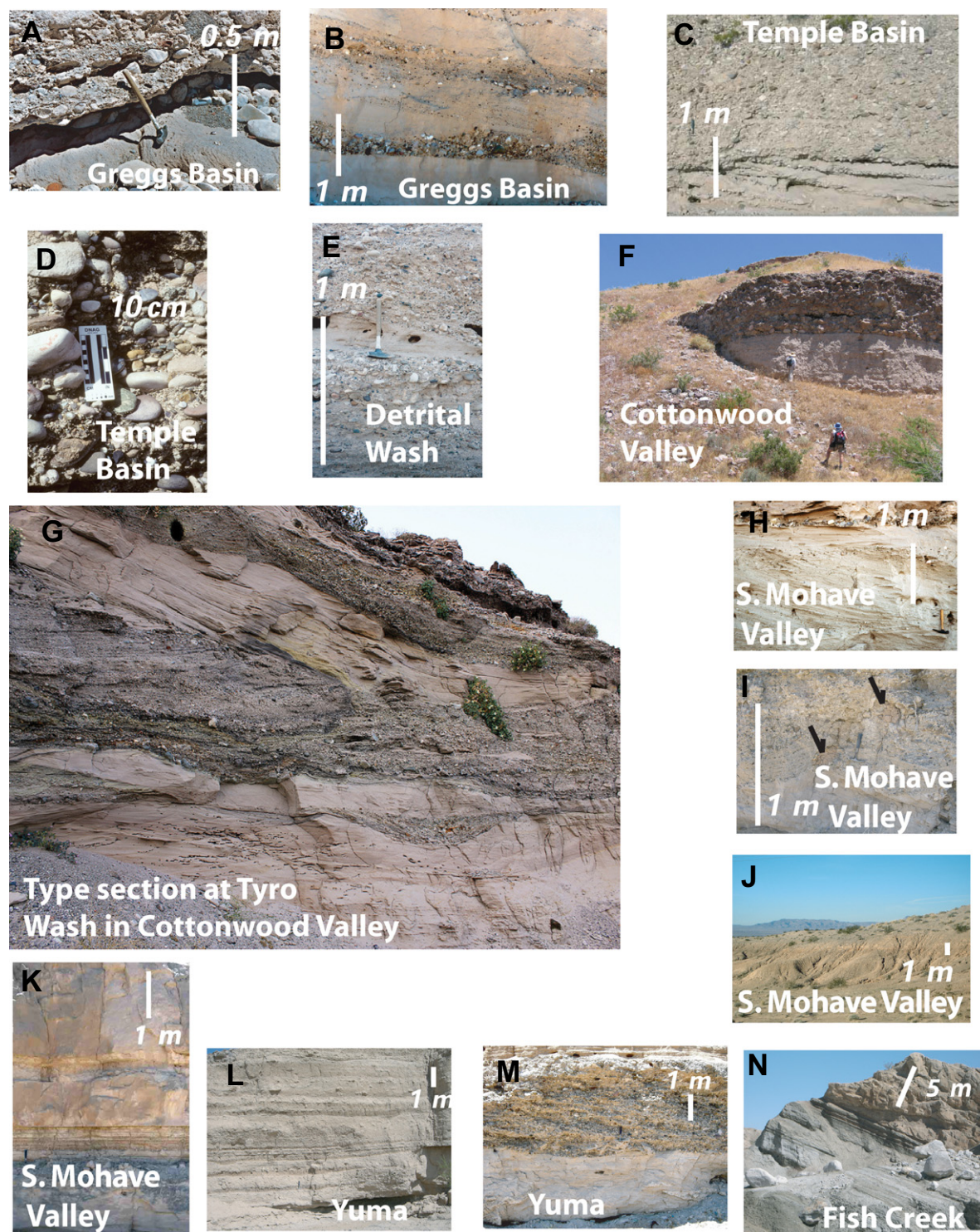


Figure 8. Photographs of Bullhead Alluvium (E–K) and probably correlative Pliocene Colorado River fluvial sediments, arranged from upstream to downstream. (A–B) Conglomerate and cross-bedded sandstone stratigraphically above 4.4 Ma basalt of Sandy Point. (C) Imbricated conglomerate and underlying cross-bedded sandstone. (D) Typical conglomerate showing roundness. (E) Interbedded conglomerate and sandstone. (F) Boulder conglomerate resting on light-toned Miocene fanglomerate. (G) Cross-stratified sandstone and conglomerate in the proposed type section. (H) Cross-bedded pebbly sandstone. (I) Cross-bedded sandstone and conglomerate containing 0.3 m clay balls (arrows). (J) Interbedded clay and fine sand and overlying loose sand high in the Bullhead Alluvium (270 m above sea level). (K) Cross-bedded sandstone and mudstone interbeds (Sacramento Wash). (L) Interbedded very fine sand, silt, and silty clay. (M) Cross-bedded conglomerate and sandstone. (N) Reddish, thick-bedded, cross-bedded C-suite sandstone typical of Arroyo Diablo Formation above gray, thinner-bedded, biotite-rich, locally derived interbeds typical of Olla Formation.

Colorado River sediments along the valley margins, and tributary valleys exhibit their own fluvial clast assemblages (e.g., arkosic sands along Sacramento Wash, and rounded pebbles including sandstone, volcanics, and jasper along the Gila River Valley).

Coarse sediment including cross-bedded gravels (Fig. 8) and imbrication and cross-bedding directions that indicate downstream accretion are consistent with sediment-choked braided stream environments (e.g., Leopold et al., 1964; Miall, 1977; Nations et al., 2009). The exposed sedimentary character suggests a braided river environment dominated by coarse sand and some gravel, with tributary contributions and fluvial backfilling up some tributary valleys.

Alluvial Sections in the Salton Trough

Sections of Colorado River alluvial deposits in and adjacent to the Salton Trough, which occupy a similar stratigraphic position as the Bullhead Alluvium, are thicker and more conformable than upstream sections (Fig. 7). Subsurface Colorado River deposits drilled in the Fortuna and San Luis Basins were largely included in a thick sand-dominated alluvial unit called the “wedge zone” for its overall geometry by Olmsted et al. (1973; Figs. 6 and 7). A thinner overlying coarse gravel unit may also partly correlate to the Bullhead Alluvium. Colorado River alluvial deposits in the Altar Basin subsurface were characterized by Pacheco et al. (2006) as their “sequence C.” The Arroyo Diablo Formation in the Fish Creek–Vallecito Basin consists largely of fluvial sandstone (Fig. 8N) and interbedded red mudstone and contains an abundant vertebrate fauna and a rich floral assemblage, including the same flora as identified from fossil wood in Colorado River sediments at Yuma (Remeika et al., 1988; Nations et al., 2009). Southeast-directed paleocurrent indicators in the Arroyo Diablo Formation restore to positions south of Yuma and demonstrate that the delta plain drained southward and was south of the mouth of the river corridor near the Yuma area past 3 Ma, even as plate-boundary faulting was translating the delta closer to the Yuma area (Winker and Kidwell, 1986, 1996).

Sub-Bullhead Unconformity as a Colorado River Profile after Initial River Incision

The lowest positions of the unconformable base of the Bullhead Alluvium, measured near the valley axis, define a sloping envelope of points designated on Figure 3A as Bullhead profile I. We bracket its position between the lowest Bullhead Alluvium outcrops (near modern

river level) and the lowest subsurface positions of undated Colorado River sediments over bedrock, the Bouse Formation, and Miocene rocks. The profile has a roughly even gradient, except at faulted basins in the upper Lake Mead area and in central Blythe Basin, where it dips below sea level.

We interpret this profile, except where faulted or subsided, to mark the approximate early Colorado River profile after incision of the divides separating Bouse Formation basins. The Colorado River’s evolution from a series of Pliocene lake basins to an integrated river represents a complex response of a fluvial system to massive sediment influx combined with step-wise integration (Pearthree and House, 2014). We infer that profile I was reached only after an integrated river carrying bed-load tools was able to incise older interbasin divides down to an ultimately smoother profile. Bullhead profile I marks the river’s transition to Bullhead aggradation.

The Bullhead I profile and its inset into older lake deposits indicate substantial valley incision. The Bullhead Alluvium and probable correlates lie as much as 220 m (Greggs Basin) to 460 m (Grand Wash Trough) lower in elevation than nearby exposed Hualapai Limestone. Downstream, the profile is lower than uppermost Bouse Formation remnants of basin-fill facies by 285 m in Cottonwood Valley, ≥ 230 m in Mohave Valley, and ≥ 230 m in Lake Havasu Basin, and probably ≥ 200 m in northern Blythe Basin. The bottoms of Bouse lakes were lower than the highest of these Bouse Formation deposits, based on internal structural basinward dips and subsided elevations in the formation in Blythe Basin, and soft-sediment folds and slumps having basinward vergence in Mohave Valley and Blythe Basin. The present-day elevation differences of Bullhead profile I below Bouse Formation outcrops of basin-fill detritus therefore only roughly approximate the erosional inset into the Bouse Formation.

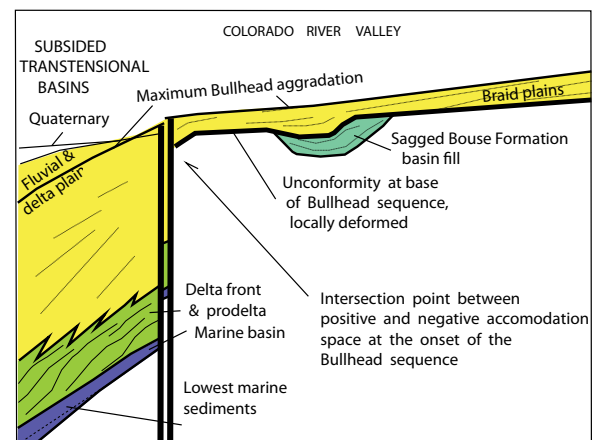
The erosional unconformity at the base of the Bullhead Alluvium is observed at least as far downstream as northern and southern parts of the Blythe Basin. It disappears somewhere between there and the conformable Fish Creek section, which records continuous deposition from deltaic marine into fluvial deposits without erosional breaks. As in the Fish Creek section, undated subsurface sections in the Altar, San Luis, and Fortuna Basins also shift from deltaic marine up section to fluvial sections (Figs. 1, 2, 6, and 7). The intersection point (Weissman et al., 2002) for Bullhead profile I, where pre-Bullhead erosion transitioned downstream to continuous deposition, may coincide with plate-boundary faults that adjoin the thick subsided and translated sections in the Salton Trough (Fig. 9).

Top of Bullhead Alluvium

The correlations in various basins enable us to reconstruct the maximum elevations of Bullhead Alluvium along the river corridor, >200 m higher than Bullhead profile I. Bullhead profile II on Figure 3A envelops these high outcrops, and we consider it to represent the depositional top of the Bullhead Alluvium paleovalley fill. Reconstructing this fill by projecting across the modern valleys suggests maximum pre-eroded formational thicknesses up to 250–300 m. The base of the Bullhead deposits outlines paleovalley shapes similar to the modern topography.

Exposures high on wide valley flanks indicate that at the peak of its aggradation, the Bullhead Alluvium filled the valleys along the river corridor with alluvial braid plains (Fig. 2). Southward-directed current imbrication and cross-bedding in Bullhead strata in Detrital Valley and Temple Basin indicate that these cross valleys were progressively backfilled as aggradation expanded many kilometers away from the river valley’s westward course. These observations

Figure 9. Stratigraphic model of Pliocene Colorado River-derived facies from the Blythe Basin into the Salton Trough. Sediments were dominantly supplied by the Colorado River; local tributary alluvium not shown separately. We infer that abrupt thickening of sections into the Salton Trough (Fig. 7) relates to complex transtensional faulting and subsidence along the plate boundary.



provide evidence that braid plains filled in low areas and more-or-less leveled the valley widths along the river corridor as the aggradation progressed. Figure 2 projects the level of Bullhead profile II onto present topography to estimate the original extent of the deposits as wide as 50 km in the river corridor. The Colorado River delta plain in addition filled much of the Salton Trough (e.g., Muffler and Doe, 1968).

Timing of Bullhead Aggradation

Bullhead profile I must postdate the demise of the ca. 4.83 Ma sediment-trapping Bouse Formation lake in the Blythe Basin. Final integration of the Colorado River carrying bed load to the Salton Trough may be recorded in the Fish Creek–Vallecito Basin, where sustained Colorado River–derived sedimentation began ca. 4.8 Ma (Dorsey et al., 2011). An earlier short-lived pulse of Colorado River–derived sand to the Fish Creek–Vallecito Basin correlated to 5.3–5.1 Ma (Dorsey et al., 2007, 2011) remains enigmatic.

Age constraints in Cottonwood and Mohave Valleys date the Bullhead Alluvium as younger than the Bouse Formation and underlying 5.6 Ma tephra and older than a 3.3 Ma tephra. Tephrochronology on two tephra beds in Mohave Valley provided the most direct constraints on the Pliocene age of the formation. A tephra assigned a correlation age of 4.1 ± 0.5 Ma lies in the upper 10 m of the formation in a piedmont fan-gravel interbed, whereas the 3.29 ± 0.05 Ma Nomlaki Tuff forms a bed in a post-Bullhead piedmont fan deposit inset at least 50 m below the highest Bullhead Alluvium (House et al., 2008b; Table 1; Fig. 3B). Matmon et al. (2012) calculated a 4.1 ± 0.3 Ma minimum cosmogenic-isotope burial age for Bullhead Alluvium low in the section in Mohave Valley.

Dates elsewhere help to constrain the age of the Bullhead Alluvium and related deposits. The basalt of Sandy Point, dated as 4.41 ± 0.03 Ma, forms a lava-flow layer within a 60-m-thick gravelly Colorado River section in Gregg's Basin (Faulds et al., 2001; Howard et al., 2008). Matmon et al. (2012) calculated a 3.6 ± 0.5 Ma burial age for Colorado River sediments perched above Hoover Dam. Their elevation projects toward upper levels of the Bullhead Alluvium (Fig. 3B). An assemblage of petrified wood in strata tentatively assigned to the Bullhead Alluvium near Yuma was correlated to a similar assemblage in the Pliocene Arroyo Diablo Formation (Nations et al., 2009).

Paleomagnetically studied sections of unit QTrb (probable Bullhead Alluvium) in the Blythe Basin were found to be dominantly reversed, with normal intervals, and were ten-

tatively correlated to the Gilbert polarity epoch (Kukla and Updike, 1976). The related Arroyo Diablo Formation in the Salton Trough (Figs. 1 and 6) accumulated more than 1300 m of reversed-polarity fluvial thickness from ca. 4.25 Ma to 3.6 Ma during the Gilbert epoch, and another 1000 m during subsequent normal and reversed polarity intervals of the Gauss polarity epoch by 3.0 Ma (Dorsey et al., 2011). As explained later herein, we infer that the 4.25–Ma base of the Arroyo Diablo Formation predates the culminating longitudinal profile of Bullhead aggradation.

In our interpretation of the age constraints (Table 1), deposition of the Bullhead Alluvium was under way by 4.4 Ma (basalt-flow age) in Gregg's Basin and reached its highest aggradation level in the reach from Hoover Dam to Mohave Valley after 4.1 ± 0.5 Ma (tephra age) and 3.6 ± 0.5 Ma (burial age) and before 3.3 Ma (tephra age). The Bullhead aggradation pulse in the Colorado River corridor is constrained between 4.8 and 3.3 Ma, and we assume it mostly spanned from ca. 4.5 to 3.5 Ma. Fluvial sedimentation continued in the Fish Creek–Vallecito Basin after this upstream aggradation ended.

Deformation

Deposits along the lower Colorado River corridor and in the Salton Trough exhibit evidence that allow us to address deformation on both local and regional scale. Careful future structural work could better quantify some fault throws and their effect on the Bullhead Alluvium and correlative strata. In addition to the deformation discussed here, other faulting was documented upstream in Grand Canyon, with significance for fault uplift of parts of the Colorado Plateau (e.g., Karlstrom et al., 2007, 2008; Reesor and Seixas, 2011; Crow et al., 2014).

Northern Basins

Folded Pliocene alluvium sections in Boulder, Gregg's, and Blythe Basins and Cottonwood and Mohave Valleys record local syn-Bullhead and younger deformation. Post-Miocene faulting of the Hualapai Limestone on the Wheeler fault uplifted the Grand Wash Trough and the western Grand Canyon block relative to downstream areas to the west (Lucchitta, 1966; Howard and Bohannon, 2001; Karlstrom et al., 2007, 2008; Reesor and Seixas, 2011). Fault throw of 375 m combined with reverse-drag flexure toward the fault from both sides resulted in a net relative uplift of the Hualapai Limestone 150 m higher in eastern Grand Wash Trough than in Temple Basin and Detrital Valley (Howard et al., 2000). If the fault slipped at a constant

rate since 6 Ma, then Bullhead profile I could have experienced ~110 m of regional uplift east of the Wheeler fault since 4.5 Ma, and Bullhead profile II would have experienced ~90 m of regional uplift since 3.5 Ma. In Gregg's Basin, 4.7 Ma and 4.4 Ma basalts dip east, and two Colorado River paleovalley fills (at Jumbo Pass and Gregg's Hideout–Spring Canyon) slope eastward, all consistent with post-Bullhead continued rollover folding and Wheeler fault normal offset (Lucchitta, 1966; Wallace et al., 2005; Howard et al., 2000, 2003, 2008). The southern part of the Wheeler fault system offsets Lower Quaternary fan deposits (Lucchitta, 1966). Crow et al.'s (2014) calculated river incision rate of ~100 m/m.y. in the western Grand Canyon block averaged since 3.9 Ma is consistent with relative uplift of the western Grand Canyon block on the Wheeler fault.

The highest mapped remnants of Colorado River conglomerate in the Grand Wash Trough (Lucchitta, 1966), however, are lower than some Colorado River alluvium that we tentatively include in the Bullhead Alluvium in Temple Basin and only <95 m higher than the downfolded 4.4 Ma section in Gregg's Basin (Fig. 3). As a further contradiction to expected relative uplift of the east side of the Wheeler fault, some outcrops that we tentatively include in the Bullhead Alluvium in Gregg's and Temple Basins west of the fault exceed the elevation of a contemporaneous(?) water-table speleothem upstream in Grand Canyon that Polyak et al. (2008) inferred to record river level and dated using U–Pb as 3.87 ± 0.10 Ma (Fig. 3B). Whether or how much the Bullhead Alluvium is relatively upthrown eastward on the Wheeler fault is therefore left uncertain.

The longitudinal profile (Fig. 3) reveals that Colorado River deposits exposed in Temple Basin and Bullhead Alluvium in Detrital Valley range in elevation ~200 m higher than the folded, now-mostly drowned Bullhead Alluvium in Boulder Basin to the west. The apparent offset implies that Detrital Valley and Temple Basin were uplifted ~200 m by fault offset relative to Boulder Basin and downstream sections (Figs. 3 and 4). We generalize the offsetting structures as the Callville fault of Longwell (1936; Fig. 3B), while recognizing that they may include faults in Detrital Valley. Folding and angular unconformities within the Bullhead Alluvium in Boulder Basin likely relate to this faulting (Longwell, 1936; Anderson, 2003). Further work on the geometry and offset history on these faults and on the Wheeler fault system would help to better assess uplift of the eastern Lake Mead area and the western Grand Canyon block relative to the lower Colorado River corridor (e.g., Karlstrom et al., 2007).

Local structures that deform the Bullhead Alluvium on the east flank of southern Mohave Valley include a 20 m down-to-basin monocline above a buried fault, possible structural lowering of subsurface gravels beneath the nearby Colorado River floodplain, and fanning dips and small angular unconformities (Fig. 4; Metzger and Loeltz, 1973; House et al., 2005; Pearthree et al., 2009; Howard et al., 2013). Minor normal faulting continued into the late Pleistocene (a few meters offset; Pearthree et al., 1983).

Southern Blythe Basin

Metzger et al. (1973) interpreted their subsurface correlations to indicate that their unit B and underlying Bouse Formation are subsided in the central part of the Blythe Basin, with the contact between them reaching a depth of at least 62 m below sea level or possibly 100 m below sea level (Fig. 4; Palo Verde). If this part of unit B indeed correlates to the Bullhead Alluvium and was deposited above Pliocene sea level, its depressed base would require that it and the underlying Bouse Formation have subsided as much as >100 m below Pliocene sea levels. Bouse Formation at the north and south ends of the Blythe Basin (near Parker and near Cibola) underlies Quaternary alluvium at shallow depths (Metzger et al., 1973; blue Xs in Fig. 3) and apparently is not subsided in those areas. A bedrock canyon at Parker Dam filled with Colorado River alluvium bottoms at 40 masl and precludes the possibility of any deeper subsided Bullhead Alluvium at that location (Berkey, 1935b; Metzger et al., 1973).

Basinward dips in the Bouse Formation in the Blythe Basin appear to reflect structural sagging in some areas, in addition to common primary dips of the basal parts of the formation due to sediment draping on the underlying valley sides. Basinward structural dips of 2°–8° are measured in exposed laminated marl in the Bouse Formation (Buising, 1990; Homan and Dorsey, 2013). Recent observations of the Bouse in the southeast part of the Blythe Basin by Homan and Dorsey (2013), Homan (personal commun., 2014) and us reveal systematic basinward wedging or divergence of stratal surfaces, which suggest 1°–1.5° of tilting toward the basin axis during deposition. We judge also that gentle basinward dips of geophysically logged and correlated subsurface beds and horizons in the interbedded (basin-fill) facies of the Bouse Formation on the west flanks of the Blythe Basin record sagging (e.g., Palo Verde section of Fig. 4; Woodward-McNeil & Associates, 1975; Fugro, 1976).

A greater elevation regularity of uppermost exposures of both the Bullhead Alluvium and the Bouse Formation on the range flanks com-

pared to low, valley-axis occurrences (Spencer et al., 2013) can be interpreted to suggest that the axial parts of the valleys have subsided more than the valley flanks and adjacent bedrock ranges (Figs. 3 and 9). Some basinal sagging may have occurred during deposition of the Bouse Formation and Bullhead Alluvium. If so, the top of these formations in valley axes may have been lower than the maximum elevations determined from basin-margin outcrops (e.g., Bullhead II profile in Fig. 3). Sediment loading and differential compaction undoubtedly contributed to basinal sagging. The underlying Bouse Formation is as much as 233 m or more thick (Metzger et al., 1973) and might be expected to have been compacted by 30%–40% as its silt-clay-sand transformed to claystone and shale (assuming typical densities from Daly et al., 1966). The basinward dips, basin subsidence, an ~46 m down-to-basin fault offset of Bouse Formation on the SE margin of Blythe Basin (Metzger et al., 1973), and smaller faults (e.g., Carr, 1986) provide evidence that the Blythe Basin experienced post-Bouse deformation. Paleo-isostatic rise and fall of the crust as it adjusted to water and sediment loading and unloading would further affect the relation of elevations to stratigraphy.

Colorado River sandstone and conglomerate, mapped by Stone (2006) at 230 masl 13 km northwest of Palo Verde (in the Mule Mountains), overlook and project 90 m above a broad pass that separates the Blythe Basin from the closed Chuckwalla Valley to the west, which bottoms another 30 m lower (Fig. 2). Unless the pass was once high enough to confine the Blythe Basin, aggrading Colorado River sediments would have overtopped this pass and filled Chuckwalla Valley. Like Fugro (1976), we suggest that Chuckwalla Valley has been tectonically lowered, along with any contained Bullhead Alluvium and Bouse Formation.

Salton Trough Basins

Large thicknesses of Pliocene Colorado River-derived sediment accumulated in the fault-bounded basins of the Salton Trough as they subsided (Fig. 7). “Wedge zone” Colorado River alluvium thickens, and its subsided base deepens rapidly both southeast from Yuma in the Fortuna Basin and southward from Yuma in the San Luis and Altar Basins, which are separated from the Fortuna Basin by a buried basement ridge along the Algodones fault (Olmsted et al., 1973; Dickinson et al., 2006). Thick deposits of Colorado River alluvium in these basins are now subsided to depths as great as 578 m below sea level (mbsl) in the Fortuna Basin, 936 mbsl in the San Luis Basin, and 2970 mbsl in the Altar Basin (Fig. 7; Olmsted et al., 1973; Eberly and

Stanley, 1978; Pacheco et al., 2006); alluvial interbeds in the underlying transitional deltaic zone are even deeper.

The Algodones-Altar fault(s) lies on strike with the San Andreas fault and likely was the major plate boundary for most of the last 6 m.y. Restoration of dextral plate-boundary slip on this and other faults of the San Andreas system reconstructs the San Luis, Altar, Fish Creek–Vallecito, and Laguna Salada Basins to originally distal positions south of Yuma (Fig. 1; Winker and Kidwell, 1996; Pacheco et al., 2006). Syndepositional subsidence by extensional detachment faulting led to thick accumulations (Pacheco et al., 2006; Dorsey et al., 2011; Martín-Barajas et al., 2013). The offset Fish Creek–Vallecito Basin records ~5 km of syndepositional subsidence in the hanging wall of a detachment fault (West Salton detachment fault) before ca. 1.1–1.3 Ma, when the section was uplifted along modern strike-slip faults (Janecke et al., 2010; Dorsey et al., 2011, 2012).

Longitudinal Profiles of the Bullhead Alluvium

The longitudinal distribution of Bullhead elevations (Fig. 3) shows that the Bullhead Alluvium, including tributary contributions, aggraded the river valley >200 m from Temple Basin to Yuma. We consider Bullhead profiles I and II to approximate the river valley profiles at the beginning and end of Bullhead aggradation. By the nature of the data, the Bullhead profile II is a valley, or valley-bottom, profile, and not exactly a longitudinal river profile. Upstream reaches of the lower Colorado River likely reached their maximum level of aggradation earlier than downstream reaches, and they likely were somewhat incised as aggradation continued downstream. The composite profile of the highest levels of aggradation along the river thus would be diachronous and a bit steeper than the longitudinal profile ever actually was.

The Bullhead I and II profiles and intermediate aggradation stages of the Pliocene Colorado River presumably each ended downstream at a tidally influenced bayline in the delta (Shanley and McCabe, 1994). We assume that Bullhead profile I records incision and smoothing of an initial post-Bouse integrated river profile. Bullhead profile II records the culminating peak of aggradation in the river corridor, before younger incision relowered the river profile. The two profiles roughly parallel each other, except in the deformed Blythe Basin, but they tend to converge downstream. This convergence is consistent with an upstream cause for the fill: excess sediment supply relative to carrying capacity (Fig. 3). Lower younger profiles, including that

of the modern river, reflect post-Bullhead incision and subsequent smaller aggradation-degradation cycles.

The river profiles indicated by the top and bottom of the Bullhead Alluvium resemble the slopes of Quaternary profiles of the Colorado River defined by the modern river and by the 70 ka Chemehuevi Formation. Both the modern river's longitudinal profile and the profile defined by the base of the Chemehuevi Formation aggradation sequence (Fig. 3B) roughly resemble Bullhead profile I from Boulder Basin downstream, with the exception of the anomalous dip in profile I in Blythe Basin.

Uppermost exposures of the Bullhead Alluvium (Bullhead profile II in Fig. 3) define an average modern elevation gradient for the maximum Bullhead aggradation of ~0.5 m/km from Hoover Dam to Yuma (Table 2). This long reach of the river lacks major tributaries, consistent with a nearly linear river gradient. The plotted river distance (Fig. 3), because of meandering and anastomosing, is ~20% longer overall than valley distance as measured by Malmon et al. (2011). A braided sand-and-gravel Bullhead Alluvium river bed would have been straighter (and shorter and steeper), but by no more than 20% compared to the modern winding river distances measured in Figure 3, so the Bullhead profile II gradient did not exceed ~0.6 m/km (using valley distance; Table 2).

A 0.5–0.6 m/km down-valley gradient is steeper than the (anastomosing) modern river (0.3–0.4 m/km) and approximately matches that of the aggraded upper limit of the Pleistocene Chemehuevi Formation (Table 2; Fig. 3B; Malmon et al., 2011). The Chemehuevi Formation thickens upstream, like the Bullhead Alluvium, and Malmon et al. (2011) interpreted its aggradation as driven from upstream by an increased supply of sand-rich bed-load material relative to carrying capacity. The slope of its aggraded profile exceeds the historic river's profile, which caps a Holocene aggradation that may have been a response to eustatic rise of base level downstream (Howard et al., 2011). The profile of maximum elevations of the Chemehuevi Formation exceeds the depositional slope defined by tephra beds (Malmon et al., 2011)

and appears to become younger downstream, as we suggest the Bullhead profile II also does. If sediment supply and carrying capacity were similar, a sand-and-gravel Bullhead river would be expected to have a similar or slightly steeper slope than the finer-grained Chemehuevi river.

A strength of examining the Bullhead aggradation through its longitudinal profiles over hundreds of kilometers of valley length is the ability to evaluate possible broad-scale deformation. The upper profiles of the Bullhead and Chemehuevi Formations were most likely formed in relatively brief intervals and thus are useful markers for fault displacement, tilting, uplift, and subsidence. Karlstrom et al. (2007, 2008) used profiles of the Colorado River and estimates of its incision at selected spots together with analysis of fault offsets to construct models of deformation of the river's path through Grand Canyon and into the lower Colorado River corridor. Our analysis of the lower Colorado River corridor expands the data available about positions of the incised base of the Bullhead Alluvium (Bullhead profile I) and especially emphasizes the top of the aggradation as a key datum.

We consider the essentially identical gradients for the Bullhead and Chemehuevi aggradation sequences, despite more than 3 m.y. age difference, as unlikely to result from chance tilting that equalized different initial slopes. Instead, they likely reflect similar initial slopes. This interpretation leads us to a key conclusion that the Bullhead Alluvium is not substantially up-tilted over the broad region from Yuma to Hoover Dam, 390 km north and closer to the Colorado Plateau. Uncertainties in Bullhead profile II (Fig. 3; Table 2) and the prospect from its coarse grain size that its gradient could have been initially slightly steeper than the finer grained Chemehuevi Formation aggradation profile allow the possibility that Bullhead profile II has been tilted up relatively southward, but not likely by more than a few tens of meters.

If Bullhead profile II in Figure 3 is projected downstream from the Algodones fault, it intersects Pliocene sea levels ~300–450 river kilometers downstream. This is roughly twice as far from Yuma in (winding) river distance as both the modern mouth of the river and the restored

position of the 4.25 Ma marine-alluvial transition at the base of the Arroyo Diablo Formation (Fig. 1).

The pre-eroded volume of the Bullhead Alluvium between the Grand Canyon and Yuma is on the order of 10^3 km^3 . It represents stored river bed load and some tributary debris, and it would have been greatly exceeded by through-flow of bed load and finer-grained wash load passing through the valley and out to sea. For comparison, a volume of 10^3 km^3 corresponds to about $\sim 10^4$ yr of both the predam river's historic sediment load and the estimated long-term average ($\sim 70 \times 10^3 \text{ km}^3/\text{m.y.}$) delivered by the river to the Salton Trough over the last 5 m.y. (Dorsey, 2010; Dorsey and Lazear, 2013).

POST-BULLHEAD DEGRADATION AND YOUNGER CYCLES

Pliocene and Pleistocene piedmont alluvial fans successively inset into the Bullhead Alluvium on the valley flanks record long-term lowering of the valley floor after the climax of Bullhead aggradation, beginning by at least 3.3 Ma (House et al., 2008b; Fenton and Pelletier, 2013). Like Bullhead profile I, this re-incision transitioned downstream to continuous deposition in the delta. Inset fluvial deposits indicate that post-Bullhead degradation eventually returned the grade of the lower Colorado River to near its pre-Bullhead elevations, to which it recurrently returned following younger perturbations.

Three younger fluvial aggradation episodes along the river were all smaller than the Bullhead episode. An undated Pliocene or Pleistocene boulder conglomerate, ≥ 30 m thick with a basal thalweg 15 m above the historic river grade in Mohave and Chemehuevi Valleys, records a post-Bullhead cycle of incision and then aggradation, possibly in a single flood (Howard and Malmon, 2011). The following two younger late Pleistocene and Holocene aggradation sequences are finer grained than the Bullhead sequence. The lowest base of the Upper Pleistocene Chemehuevi Formation near the historic river's grade defines a re-incision river profile (House et al., 2005; Howard et al.,

TABLE 2. COLORADO RIVER GRADIENTS, HOOVER DAM TO YUMA

Age	Elevation drop (m)	Gradient using river distance of 519 km (m/km)	Gradient using valley distance of 453 km (m/km)
Predam twentieth-century Colorado River	165	0.32	0.36
Top of Chemehuevi Formation aggradation sequence (0.07 Ma)	258	0.50	0.57
Bullhead profile II (ca. 3.5 Ma)*	274	0.54*	0.62*
Bullhead profile II assuming unverified Colorado River outcrops as high as 225.5 m above sea level near Yuma reported by Olmsted et al. (1973).**	227.5	0.44**	0.51**

*For outcrops near Yuma, we use river distance 506 km and valley distance 443 km.

**For outcrops near Yuma, we use river distance 509 km and valley distance 446 km.

2013). The Chemehuevi Formation aggradation raised the river's grade as much as 140 m (Fig. 3B; Malmon et al., 2011). Inset post-Chemehuevi Formation sediments show that, later, the river re-incised to a pre-Holocene grade at least 30 m below historic river grade, likely related to low sea levels at the Last Glacial Maximum. Subsequent aggradation deposited at least 30 m of sand and silt from 8 to 4 ka, culminating in the modern floodplain (Metzger et al., 1973; Howard et al., 2011).

DISCUSSION

The Bullhead Alluvium and its correlative deposits indicate substantial aggradation of the lower Colorado River valley soon after the river became connected with and carried bed load to the Gulf of California. This episode of aggradation was the largest since river integration; nevertheless, it has common elements with subsequent aggradation episodes. Whatever its ultimate cause, the Bullhead aggradation remains a singularity in the origin of the river. Strata deposited in the Bullhead episode are much deformed in the Salton Trough and are sagged or faulted in local basins along the river corridor, but we argue that the regional slope of profile II from Yuma to Hoover Dam records little or no regional tilting or uplift in the last 3.5 m.y. In this section, we discuss possible causes and implications of the Bullhead aggradation.

We infer that numerous Colorado River deposits along the lower Colorado River corridor collectively record a single Bullhead aggradation sequence, as can be demonstrated best for the deposits in Mohave and Cottonwood Valleys, but uncertainties remain. Sections we infer as Bullhead Alluvium locally may overlap with sediments stranded during pre-Bullhead incision or pre-incision supra-Bouse deltas. Misidentifications could affect our interpretations of faulting on the Wheeler and Callville faults and sagging in the Blythe Basin. Although we treat Bullhead profiles I and II as snapshots in time, both profiles probably were time transgressive. Bullhead aggradation likely began in upper basins during final incision downstream, and the end-Bullhead re-incision likely began upstream even as deposition was culminating downstream.

The pulse of aggradation represented by the Bullhead Alluvium may have had one or more causes, including regional and local tectonic deformation, tectonic damming, sea-level change, and changes in river length and gradient driven by sediment supply. We consider these in turn.

One possible explanation for the Bullhead Alluvium is regional subsidence of the lower

Colorado River valley, resulting in broad valley aggradation graded to Pliocene sea level. Bullhead profiles I and II were each likely graded to Pliocene sea levels. If the accommodation space needed for aggradation had come from regional subsidence of Bullhead profile I, an equal and compensating younger uplift would be needed to raise Bullhead profiles I and II to their modern positions from Yuma to Hoover Dam, 500 river kilometers. This region is 300 km wide measured normal to the plate boundary. Subsidence or uplift is an expectable process for the plate-boundary setting of the lower Colorado River corridor, but we consider broad regional uplift following and *closely compensating* for subsidence, with little or no net tilting, over this wide region as unlikely.

Could tectonic damming downstream along the plate boundary have formed an elevated base level in the Salton Trough to which Bullhead profile II might have graded? The sedimentary record in profile II exposures and downstream from them argues against this possibility. Colorado River-derived deposits in downstream basins at Fish Creek and (undated) in the Altar and San Luis Basins are thick and record continuous syndepositional subsidence, not any uplifted paleodams. The Fish Creek–Vallecito Basin records continuous and voluminous deposition of Colorado River–derived sediment from ca. 4.8 to 2.9 Ma during the time of Bullhead Alluvium deposition (Dorsey et al., 2011), lacking any apparent interruption from damming. A river the size of the Colorado could be expected to quickly defeat temporary tectonic blockages. Further, if a temporary tectonic blockage had raised the river's base level, the resulting lowered river gradient might be expected to produce fining of proximal aggrading sediments, yet sandstone and conglomerate dominate the exposed Bullhead section near Yuma. We conclude therefore that the Bullhead river was not tectonically dammed.

The thickness and elevation ranges of the Bullhead Alluvium far exceed modeled Pliocene sea-level fluctuations (<30 m; Raymo et al., 2009). Sea-level changes, therefore, are unable to explain the Bullhead aggradation.

We instead suggest that the Bullhead aggradation records steepening and lengthening of the river profile. The tendency for profiles I and II to converge downstream (Fig. 3) may reflect aggradational steepening of a sediment-laden river driven by upstream controls. The aggradation history focuses additionally on key fluctuations in the length of the river to the marine base level. As discussed in the following, steepening and lengthening of the Bullhead river both point to high sediment supply as the driver of aggradation.

Pliocene Shorelines and Progradation in Relation to Long Profile of Deposits

The evolving position where Colorado River alluvium entered the Gulf of California poses a key constraint on the Bullhead profiles, as it served as an approximate stratigraphic base for the evolving river. A riverbed can lengthen and build up as its delta progrades downstream during aggradation, or it can shorten and lower if the distance to the base-level decreases. The bayline and area of tidal influence upstream from the shore (Shanley and McCabe, 1994) would have served as the stratigraphic and geomorphic base for evolving pre-Bullhead river incision and aggradation. We argue that lengthening of the Pliocene river profile to this effective base level as it prograded its delta was a major control on the changing profile elevations from Bullhead profile I to Bullhead profile II, and that subsequent shortening of the river contributed to post-Bullhead lowering. Progradational lengthening of the delta and its channels by river aggradation competed with subsidence and plate-motion translations that were tending to shorten the river.

Colorado River bed-load sediment would have reached the sea continuously following the final bed-load overtopping of upstream divides and demise of Bouse Formation lakes after 4.8 Ma. The river's Bullhead profile I, except in the subsided Blythe Basin, appears to project toward Pliocene sea levels near Yuma. We infer that the Bullhead profile I river delivered sediment, including bed-load tools that had cut the profile, to a delta growing near Yuma, where marine Miocene or earliest Pliocene beds underlie estuarine beds assigned to the Bouse Formation (Smith, 1970; Olmsted et al., 1973; Winker, 1987).

The Bullhead-era river built up its bed and lengthened its longitudinal profile by rapid progradation. As the sloping river profile lengthened to a more distant sea level, the upward-sloping stream profile could migrate downstream and create accommodation space for deposition to raise upstream parts of the profile (cf. Shanley and McCabe, 1994). For sediment progradation to lengthen the subaerial delta, it had to be at sufficient rates to defeat delta subsidence (from loading plus tectonism), and it also had to overcome steady northwestern motion of the delta on the Pacific plate relative to North America.

The prograding delta plain when it reached the Fish Creek–Vallecito Basin at ca. 4.25 Ma was subsiding ~2 mm/yr, including ~40% tectonic subsidence added to compaction and isostatic response to sediment loading (Dorsey et al., 2011). Basin subsidence earlier had been ~0.5 mm/yr before ca. 4.4 Ma, and the 2 mm/yr subsidence lasted to ca. 3.1 Ma. (The

subsidence rate estimates calculated by Dorsey et al. would be slightly less assuming the Arroyo Diablo Formation delta plain reached heights of 100–150 m above sea level during the Bullhead aggradation.) More than 1500 m of Colorado River and basin-margin-stream deposits (Palm Spring Group) accumulated in the subsiding Fish Creek–Vallecito Basin between ca. 4.25 Ma and 3.5 Ma, while only 200–300 m of Bullhead Alluvium accumulated in most of the river corridor upstream.

The culmination of Bullhead aggradation in our model relates to a more distant younger bayline than the 4.25 Ma bayline. Bullhead profile II projects toward a Pliocene base level ~300–450 km in river distance from Yuma, roughly twice as far as the restored 4.25 Ma Fish Creek bayline. Bullhead profile II's distant bayline may be recorded in the subsurface transition from marine deltaic to alluvial facies in the Altar Basin (Pacheco et al., 2006; Helenes et al., 2009).

Sediment-Supply Control on the Bullhead Aggradation

The lengthening of the Bullhead river and delta and steepening of its aggrading profile point to a temporary massive overloading of sediment relative to carrying capacity. Large Bullhead sediment supply is needed to explain progradation into the Gulf of California despite rapid subsidence and northwestward tectonic translation of the delta. The submarine delta was already growing in the Fish Creek–Vallecito Basin during the pre-Bullhead incision. As high sediment supply lengthened the subaerial delta, the added accommodation space spurred aggradation along the lower river. Progradation was enough to overcome an estimated 43–46 mm/yr rate of dextral translation and 2 mm/yr of delta subsidence. Following the full aggradation, we infer that post-Bullhead incision by 3.3 Ma reflects lowered sediment supply, and the lowered profile implies a shortening of the sloping river profile to the subaerial delta. Assuming constant tectonic translation and delta subsidence, a shortening river implies that sediment supply decreased to the delta. A gradual post-Bullhead relowering of the river's longitudinal profile therefore records slowing of the high rate of sediment supply that had aggraded the Bullhead Alluvium.

Bullhead aggradation may or may not have been a direct response to integration of the Colorado River at ca. 4.8 Ma. Whether the pulse of high Bullhead sediment supply began upon full and continuous river integration to sea level or later would have important ramifications for the causes of the high sediment-supply pulse and

whether it was a direct or lagged response to integration. Younger timing constraints are not precise enough to demonstrate how diachronous Bullhead aggradation may have been along the river corridor. Timing constraints likewise are not precise enough to certify whether high sediment supply was continuous or delayed between post-4.8 Ma incision (Bullhead profile I) and the Bullhead aggradation. Steady accumulation of sediment in the Fish Creek–Vallecito Basin since ca. 4.8 Ma (Dorsey et al., 2011) suggests to us that continuous high sediment supply without a gap after 4.8 Ma is the more likely scenario.

Evolution of Longitudinal Profile

Figure 10 and Table 3 interpret stages in the evolution of the Colorado River's profile beginning after the end of Bouse Formation accumulation in the river corridor, when a large, persistent, and long-lasting flux of Colorado River–derived sediment started building the massive delta in the Fish Creek–Vallecito Basin ca. 4.8 Ma (Fig. 10A; Dorsey et al., 2011). More enigmatic, and beyond the scope of this paper, is a small volume of Colorado River–sourced sediments that somehow reached the marine Fish Creek depocenter earlier, at 5.3–5.1 Ma, before giving way to a sediment-starved interval of claystone deposition 5.1–4.9 Ma (using paleomagnetically determined ages of Dorsey et al., 2007, 2011).

We infer that Bullhead profile I records the end result of the integration of a bed load–carrying river, at the conclusion of knickpoint migration and incision of a smoothed river profile, before the Colorado River delta was built out far into the sea (Fig. 10B). As an unconformity, Bullhead profile I represents an unstable river profile (Shanley and McCabe, 1994).

Bullhead aggradation likely began as an overloaded river began aggrading its bed and lengthening the prograding delta. The ca. 4.25 Ma transition from shallow marine to fluvial delta-plain Colorado River deposition in the Fish Creek–Vallecito Basin provides a key constraint on the length of the river and its advancing delta at 4.25 Ma (Fig. 10C). The tectonically restored Fish Creek 4.25 Ma paleoshore was close to the modern river's mouth (Fig. 1), indicating that the river and exposed delta had reached lengths resembling those of today. The conclusion that the Bullhead profile II aggradation peak lengthened the river to a more distant shore (Fig. 10D, ca. 3.5 Ma) requires that the delta had prograded faster than the ~2 mm/yr subsidence and exceeded the effect of shortening by tectonic translation along plate-boundary strike-slip faults (43–45 mm/yr).

Following the subsequent 3.3 Ma lowering and inferred shortening of the river profile, continued lowering and shortening preceded the more recent smaller aggradation-degradation cycles and the historic profile of the river (Fig. 10E). Net delta expansion through geologic time evidently has tended to keep up with and on average lowered sediment supply and more-or-less matched northward translation and subsidence in the Salton Trough, because the distance from Yuma to the shoreline at the north end of the Gulf of California is about the same now as it was at 4.25 Ma.

Sources of High Sediment Supply

The newborn Colorado River that deposited the Bouse Formation and then the Bullhead Alluvium records final phases of drainage-basin integration. This integration can be inferred to have begun a process of landscape incision and unroofing of a huge area within its growing watershed. As the river incised through the lower basins, the watershed experienced base-level fall of roughly 0.5 km from the Grand Wash Trough to the marine delta, and this would have triggered a wave of upstream incision (Pelletier, 2010).

The big flux of sediment implies a spike of watershed erosion rates. An early Pliocene spike would be expected as the newly integrated river increased erosion in the high Colorado Plateau from which the river emerged (House et al., 2005), while simultaneously re-incising the lower river corridor. Uplift in the Rocky Mountains or Colorado Plateau (Duller et al., 2012; Lazear et al., 2013; Rosenberg et al., 2014; Crow et al., 2014) and possibly climatic changes related to oceanic circulation in the opening Gulf of California (Chapin, 2008) may have helped erosive potential and could have enhanced sediment delivery to the evolving river.

Some of the pulse-like sedimentation must reflect sourcing from readily available sediment stored nearby in the valleys and basins of western Grand Canyon and downstream before their re-evacuation exhausted the supply (J. O'Connor, 2014, written commun.). Their incision could cause a pulse similar to when dam removal releases a spike of sediment. Stored sediment on the order of 10^3 km³ was available to be recycled from western Grand Canyon and lower basins (cf. Spencer et al., 2013; Young and Crow, 2014). The river's incision, in addition, must have tapped into much larger volumes from Grand Canyon and upstream beyond to account for the combined Bullhead Alluvium and order-of-magnitude larger thicknesses and volumes downstream in the Salton Trough, where $5\text{--}9 \times 10^4$ km³ of

Colorado River–derived sediment including substantial sand occupies the Altar Basin and more northern basins (Fig. 7; Dorsey, 2010; Pacheco et al., 2006; Dorsey et al., 2011). Detrital zircon and cosmogenic isotope results further implicate Colorado Plateau provenance.

Modeling of detrital-zircon ages in the Bullhead Alluvium and coeval Colorado River–derived sediments suggests that Tertiary cover strata containing abundant Oligocene zircon on the Colorado Plateau provided a large source of early Pliocene sediment (Kimbrough et al., 2015). Detrital-zircon age distributions suggest that the Tertiary cover strata of the plateau were progressively eroded and stripped, while underlying Mesozoic and Paleozoic strata became denuded and exposed (Kimbrough et al., 2015; see also Fleming, 1994). Tertiary Colorado Plateau deposits, likely highly erodible, were therefore available for an early Pliocene erosional pulse.

Matmon et al. (2012) calculated watershed erosion rates as 10–40 mm/k.y. from detrital ^{10}Be analysis of Bullhead samples, rates comparable to tectonically stable regions but much slower than a rate calculated using modern Colorado River sand (~187 mm/k.y.). The slow paleoerosion rates calculated from Bullhead samples are also less than half of the estimated average post-Miocene erosion rate from the drainage area (~102 mm/k.y. using data from Dorsey and Lazear, 2013). Considering the high sediment supply needed for the Bullhead aggradation, we propose that the apparently slow ^{10}Be Bullhead-sample erosion rates were inherited from a relict late Miocene landscape. We suggest that the newly integrated Pliocene river system destabilized an old Colorado Plateau landscape of relict, slowly formed, pre-river-integration regolith, colluvium, and their locally stored detritus, and the river delivered the debris to the rapidly aggrading Bullhead Alluvium and prograding delta. Thus, we infer from the cosmogenic isotope evidence as well as the detrital zircon evidence that materials on the Miocene Colorado Plateau landscape were ripe for fast erosion when destabilized by Colorado River integration.

Regional Tectonic Implications

Our analysis of paleoriver profiles and the likely causes and consequences of initial river incision, subsequent sedimentation, and then incision again allows evaluation of regional tectonic conditions (cf. Karlstrom et al., 2007). Our interpretation—no significant regional uplift or tilting of Bullhead profiles from Hoover Dam to Yuma—is consistent with models that require no regional tilting of the underlying Bouse For-

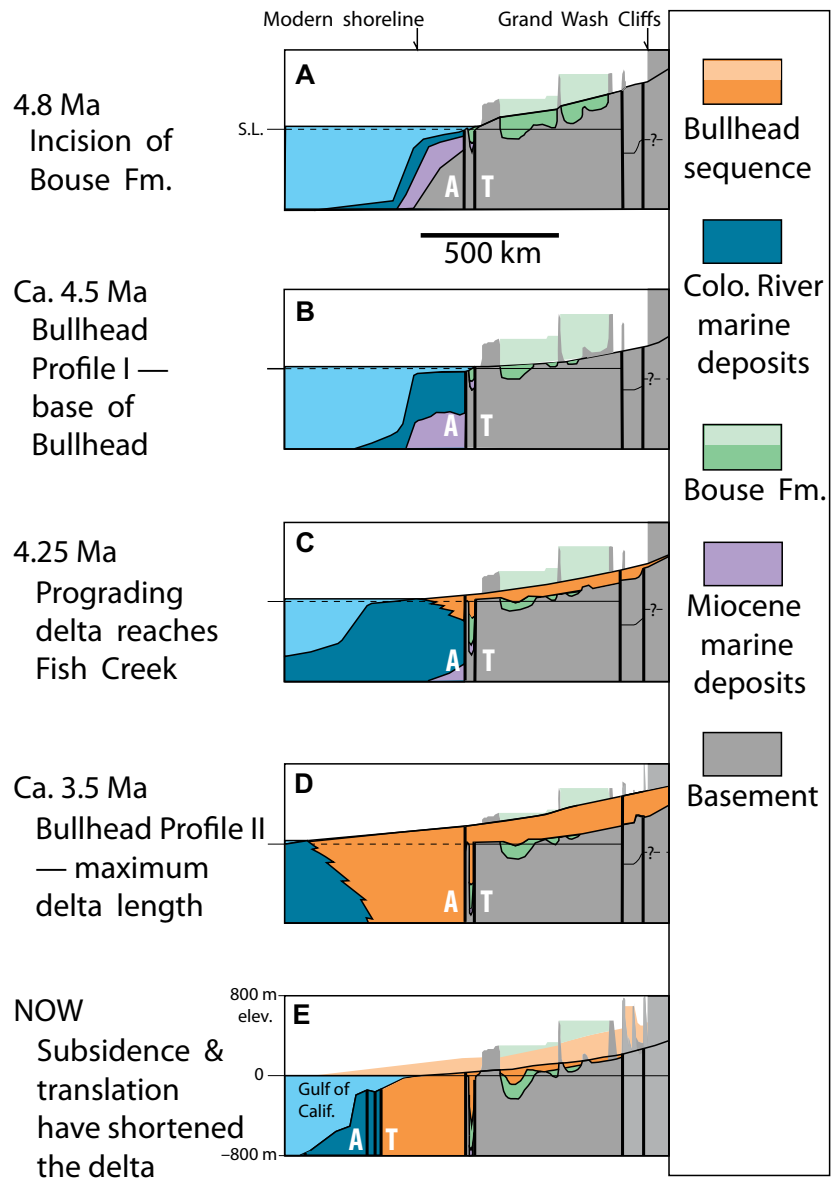


Figure 10. Interpreted evolution of the longitudinal profile of the Pliocene lower Colorado River after the demise of Bouse Formation lakes. Table 3 lists events for each panel. A and T denote San Andreas fault system translation away from (A) and toward (T) the observer, where successive major structural fault lowering and translation of the left (SW) side occur between each interval (dashed unrestored modern sea-level [S.L.] position shown for reference). Using format inspired by Karlstrom et al. (2007), positions of modern sea level to the right (upstream) of the San Andreas fault system are restored by interpreted faulting on the Callville fault and an uncertain amount on the Wheeler fault. Structural lowering near or along the Bouse Formation or equivalents is not shown where thickness and extent are uncertain in the Lake Mead area (on the right).

mation (Spencer and Patchett, 1997; Spencer et al., 2013).

Karlstrom et al.'s (2007) regional analysis of river history and faults investigated possible post-Miocene uplift of the Colorado Plateau. Even without tilting or uplift from Yuma to

Lake Mead, we infer, as in model 1 of Karlstrom et al. (2007), that normal faulting at Lake Mead caused some post-Miocene Colorado Plateau uplift relative to sea level. The offsets include the newly recognized ~200 m regional relative uplift of Pliocene Bullhead Alluvium on

TABLE 3. EVOLUTION OF LOWER COLORADO RIVER PROFILE (FIG. 10)

Panel in Figure 10	Events	Age estimate
A	Full river integration through paleolake deposits and the paleodivides that separated them. Bed-load tools degrade paleodivide knickpoints (Pearthree and House, 2015).	Ca. 4.8 Ma, the paleomagnetically correlated age of renewed and sustained arrival and steady accumulation of Colorado River–derived marine sediment in the Fish Creek–Vallecito Basin following an apparent initial pulse (5.3–5.1 Ma) and sediment-starved interval 5.1–4.9 Ma (Dorsey et al., 2011). Postdates demise of 4.83 Ma limestone deposited in a perched Bouse Formation lake (Spencer et al., 2013).
B	Incision, by further knickpoint migrations, to a smoothed longitudinal profile (Bullhead profile I) graded to the sea somewhere near Yuma, before Bullhead aggradation. Colorado River–derived sediment has accumulated 540 m thickness in the Salton Trough at the Fish Creek section, projected as near the position of the modern river's mouth but 11 km closer to the viewer.	Ca. 4.5 Ma. Precedes the beginning of fluvial aggradation including an aggradational sequence in Greggs Basin in which 4.4 Ma basalt of Sandy Point is interbedded (Faulds et al., 2001).
C	Delta has prograded as far as the Fish Creek section's position, indicating a paleoshoreline/paleobayline (as tectonically restored) approximating the same downstream distance as the modern river's mouth, overlying 1180 m of marine Colorado River–derived sediment.	4.25 Ma, the paleomagnetically correlated approximate age of transition from shallow-marine to fluvial sedimentation in Fish Creek–Vallecito Basin (Dorsey et al., 2011).
D	Culmination of Bullhead aggradation (Bullhead profile II) and delta-plain lengthening, having outcompeted delta subsidence and northward translational shortening. Subsidized section at Fish Creek (restores to a projected position near the modern river mouth but 33 km farther NW from the viewer) includes 1700–1800 m of underlying Colorado River fluvial and interbedded locally derived sediment atop marine sediment (Dorsey et al., 2011). After this culmination, lowered influx of sediment supply was unable to keep pace with subsidence and tectonic shortening of the delta, resulting in degradation in the river valley and shortening of the delta plain.	Ca. 3.5 Ma, predating post-Bullhead degradation underway at 3.3 Ma and postdating 4.1 ± 0.5 Ma tephra in upper Bullhead alluvium and gravels near Hoover Dam burial-dated as 3.6 ± 0.5 Ma (House et al., 2008b; Matmon et al., 2012).
E	The river profile experienced post-Bullhead lowering and shortening from lowered sediment supply. The modern predam profile is a net effect after continued delta building, younger aggradation-degradation cycles, and a plate-boundary shift to faults farther outboard (Martín-Barajas et al., 2013).	Now

faults grouped as the Callville fault. East-side-up offset on the Wheeler fault may have uplifted the western Grand Canyon block an additional 90–110 m, although as discussed in the following, anomalous elevations of some features across and near the Wheeler fault remain to be better explained.

Faulting that steepens a river valley can enhance upstream erosion and sediment supply, and it can subside downstream areas, thus enlarging accommodation space for aggradation. Net relative uplift of upstream reaches by faulting, such as on the Callville and Wheeler faults (Fig. 3B), would have intermittently steepened the river profile upstream from Boulder Basin, causing greater incision, knickpoint migration, and sediment liberation. A knickpoint at Grand Wash Cliffs or western Grand Canyon (e.g., Pelletier, 2010) might have contributed steepness to a Bullhead aggradation slope in the Lake Mead area.

Neither localized subsidence in the Blythe Basin nor very large fault-driven subsidence and translation in the Salton Trough along the plate boundary clearly deformed upstream segments. The Blythe Basin and Chuckwalla Valley lie in or near the broad, complex Eastern California shear zone (ECSZ, Fig. 1; Richard, 1993). The positions and ages of these two subsided basins suggest to us that they record early Pliocene continuation of transtensional deformation that created Miocene basins in the dextral Eastern California shear zone before the shear zone migrated west of the lower Colorado River cor-

ridor (Howard and Miller, 1992). Early Pliocene fault-controlled(?) subsidence of these basins likely provided accommodation space for local thickening of the Bullhead Alluvium.

The Fortuna Basin between these basins and the Algodones fault to the southwest contains much thicker, more deeply subsided Colorado River alluvial deposits (Figs. 2 and 3; Olmsted et al., 1973; Dickinson et al., 2006). The Fortuna Basin, as defined by gravity and sediment thickness, parallels the adjacent San Andreas fault system (Figs. 2 and 3; Mattick et al., 1973; Kinsland and Lock, 2001). This alignment and the basin's subsidence history are consistent with Pliocene transtensional basin subsidence related to the plate boundary. We suggest this provides additional evidence that transtensional basins developed during plate-boundary dextral shear across a zone broader than just the Salton Trough and San Andreas fault.

Implications for the Bouse Formation

The assumed incision of Bullhead profile I by a river above sea level has implications for perched outcrops of the Bouse Formation. Any marine interpretations of 100 masl Bouse Formation outcrops (McDougall and Martinez, 2014), or especially of 300 masl Bouse Formation outcrops (Metzger, 1968) in the greater Blythe Basin, would require them to be regionally uplifted from early Pliocene sea levels before the Bullhead profile I was incised toward a marine base level. The sedimentation cycles

of the Bouse and Bullhead each affected large lengths of the lower Colorado River corridor, had a similar range in elevations, and saw the eventual incision by the river to low elevations as measured in the modern topography. Our model of the Bullhead Alluvium as a sedimentary-driven cycle requires a history of localized deformation in individual basins but no regional tectonic elevation changes as far upstream as Boulder Basin. If a marine environment is confirmed for fauna in parts of the Bouse Formation that are now as high as 100 masl (McDougall and Martinez, 2014), it would suggest that our suggested regional tectonic stability since Bullhead time did not extend back in time to include deposition of those parts of the Bouse Formation.

The accumulating evidence for more local basin sagging and deformation in the Blythe Basin during and/or after deposition of the Bouse Formation and Bullhead Alluvium is a subject of ongoing research. The possibility that these sequences have locally subsided 100 m or more near the basin axis by tilting and faulting complicates current models of the Bouse Formation (Roskowski et al., 2010; McDougall, 2011; Spencer et al., 2013) that do not take the deformation into account.

Implications for Grand Canyon

Our interpretation that Bullhead Alluvium records vigorous erosion of the Colorado Plateau is consistent with deepening of upstream

canyons in response to post-6 Ma river integration. Integration of the Colorado River to the Gulf of California likely involved a significant enlargement of Grand Canyon and its tributaries. The river's entry to the Basin and Range Province onto a basin floor of Hualapai Limestone in the Grand Wash Trough after 6–7 Ma and its spill into downstream basins likely triggered major upstream incision (Pelletier, 2010).

When, how much, and how Colorado River incision affected the western Grand Canyon remain much debated (Young, 2008; Polyak et al., 2008; Wernicke, 2011; Flowers and Farley, 2012, 2013; Karlstrom et al., 2007, 2012, 2013; Lucchitta, 2013; Young and Crow, 2014). We suggest that Bullhead aggradation may have implications for this debate, because any potential backfilling of the early Grand Canyon by Bullhead Alluvium could affect interpretations of the canyon's evolution.

The western Grand Canyon was already within ~350 m of its modern depth by 3.9 Ma, according to Polyak et al.'s (2008) paleowater-table interpretation of the speleothem they dated as 3.87 ± 0.10 Ma. The date falls within the estimated span of Bullhead aggradation. The canyon's bedrock depth may have been deeper if Bullhead aggradation had already backfilled into the canyon and raised the river level. The dated speleothem and a nearby one 165–170 m lower, dated 2.17 ± 0.34 Ma, have been assumed to record levels of progressive Grand Canyon bedrock incision by the Colorado River (Polyak et al., 2008), calculated as 101 m/m.y. by Crow et al. (2014). The older speleothem's elevation of 640 m (Polyak, 2013, written commun.) or 654 m (Crow et al., 2014) lies within the elevation span of deposits in Detrital Valley that we assign to the Bullhead Alluvium and of even higher Colorado River deposits in Temple Basin (Fig. 3B). A projection of these alluvium elevations upstream from Detrital Valley would include or be higher than the older speleothem site (Fig. 3B), especially if, as seems likely, the western Grand Canyon block experienced post-Bullhead relative upthrow on the intervening Wheeler fault.

If the speleothem records river level at 3.9 Ma, it could mark an intermediate stage in the Bullhead aggradation, constrain the level of possible Bullhead Alluvium backfill at 3.9 Ma in the canyon, and raise questions about any post-3.9 Ma relative fault uplift of the western Grand Canyon block in the footwall of the Wheeler fault. Alternative interpretations could include that the speleothem's origin or its date was misinterpreted, or that our high-elevation Colorado River deposits (including at 700 masl in Temple Basin) belong not to the Bullhead aggradation but instead to remnants stranded

during pre-Bullhead incision (Howard and Bohannon, 2001). We caution for now that possible western Grand Canyon backfilling could add uncertainty to calculations of bedrock incision rate there.

CONCLUSIONS

The distribution and extent of the Bullhead Alluvium and its correlatives record the behavior of the lower Colorado River soon after its connection to the sea by way of a series of previously disconnected basin-and-range valleys extending from western Grand Canyon to the Gulf of California. The base of the Bullhead sedimentary package—the Bullhead I profile—records a graded ca. 4.5 Ma Colorado River longitudinal profile incised through interbasin divides and the Bouse Formation. Based on rough resemblance (except where locally deformed) to the modern river's grade and length, the Bullhead profile I river is inferred to have entered the northern Gulf of California in the area of the modern river's delta.

The Bullhead aggradation was a major response to the integration of the Colorado River. A temporary massive supply of bed-load sediment exceeded the carrying capacity of the river and drove the aggradation by steepening the aggrading bed, raising it >200 m (Bullhead profile II), and lengthening the delta and river. Whatever its ultimate causes, the aggradation records the lower Colorado River as fully established and carrying a very large load of bed-load sediment.

Bullhead aggradation possibly backfilled the western Grand Canyon, which would obscure the Pliocene bedrock incision history there and its relation to uplift on the Wheeler and Callville faults. Local sagging of the Blythe Basin, probably by transtension on the Eastern California shear zone, also complicates the river's evolutionary history.

We attribute the Bullhead sediment-supply pulse to (1) release of sediment stored along upper parts of the lower river corridor, (2) a wave of incision up western Grand Canyon, and especially (3) accelerated erosion of regolith, surficial deposits, and nonresistant Tertiary bedrock on a relict Miocene Colorado Plateau landscape. Whether the sediment supply was a direct or a delayed response remains to be clarified by further research on timing of events.

The Bullhead aggradation prograded and lengthened the Colorado River's delta plain into the Gulf of California fast enough to overcome both delta subsidence and northwestward strike-slip translation of the delta on the San Andreas fault system. The delta plain reached a length similar to its modern length at ca. 4.25 Ma, and

then doubled in length by the time the Bullhead aggradation peaked ca. 3.5 Ma. After that, sediment supply declined as the most erodible sources in the river catchment became exhausted, leading to degradational lowering and shortening of the lower Colorado River profile; delta progradation could no longer keep pace with combined delta subsidence and strike-slip translation.

A family of faults characterized here as the Callville fault raised Bullhead strata in the upper Lake Mead area and contributed ~200 m to apparent Colorado Plateau uplift. Our interpretation—that the ca. 3.5 Ma Bullhead II profile downstream is neither uplifted nor tilted over the 500-km-long river reach from Hoover Dam to Yuma—adds a powerful constraint to the tectonic evolution of the region.

APPENDIX 1. BULLHEAD ALLUVIUM NAME, DESCRIPTION, AND CORRELATION

Geologic maps and twentieth-century geologic reports have referred to the material making up the Bullhead Alluvium by various descriptive and informal names (e.g., Longwell, 1963; Metzger et al., 1973; Faulds et al., 2003; House et al., 2004; Pearthree and House, 2005, 2014; House et al., 2008a; House and Faulds, 2009; Malmom et al., 2009; Pearthree et al., 2009; Howard et al., 2013). The proposed Bullhead Alluvium is here named for exposures in northern Mohave Valley near Bullhead City, Arizona, and consists of deposits that were called the alluvium of Bullhead City or Bullhead alluvium by House et al. (2005, 2008b). Bullhead City takes its name from a hill known as the Bulls Head before it was flooded by Lake Mohave when nearby Davis Dam blocked the Colorado River. Additional information is given in Table A1.

Cottonwood and Mohave Valleys: Type Area

We propose typical exposures in and near Tryo Wash, east of Lake Mohave in Cottonwood Valley, Mohave County, Arizona, as the stratotype for the Bullhead Alluvium (Fig. A1A). Here, the Bullhead Alluvium spans an elevation range and projected paleothickness of 220 m, from 195 masl, where exposures disappear beneath the surface of Lake Mohave, to 415 masl, where alluvial fans truncate the formation's upper part. Approximately 20 km to the NW, a thin surface lag of Colorado River gravel lies at an elevation of 420 m. The elevation range from lakeshore outcrops in that area indicates a minimum thickness of 225 m of Bullhead Alluvium in Cottonwood Valley.

Elaborately cross-stratified, medium- to coarse-grained, light-gray fluvial sandstone and pebbly sandstone dominate the formation (Fig. 8G). Roundstone conglomerate is locally significant. The Tyro Wash section contains stacks of medium, tabular beds of trough cross-stratified roundstone gravels in excess of 5 m that are sandwiched between thick sequences of cross-stratified fluvial sand. Some locations include poorly sorted, matrix-supported beds containing mixtures of locally derived and far-traveled sediments. These are most common near the base of the unit. There are also boulder-rich, clast-supported beds in the lower part of the unit that contain locally derived boulders mixed with cobbles of exotic rock types. The local, erosive base of the unit is extensively exposed in the general area of Tyro Wash.

APPENDIX TABLE A1. STRATIGRAPHIC NOTES—PLIOCENE COLORADO RIVER SECTIONS

Area	Pre-Colorado River stratigraphy	Pliocene Colorado River stratigraphy	References
Grand Wash Trough	Hualapai Limestone 11–7 Ma interfingers with underlying mudstone and conglomerate. Limestone top is at about 860 m above sea level (masl), up-tilted to 912 masl near Wheeler fault system.	Old river gravels mapped at an estimated 370 to 520 masl are inset ~320–460 m below Hualapai Limestone.	Lucchitta (1966), Wallace et al. (2005), Faulds et al. (2008).
Greggs Basin (including Hualapai Wash)	Hualapai Limestone interfingers with underlying Miocene conglomerate; sediments are locally derived.	The deposits of Hualapai Wash conformably overlie and are downfolded with Hualapai Limestone at elevations up to 760 masl and are interpreted to represent the earliest fluviodeltaic sediments to exit from Grand Canyon before fluvial incision and Bullhead aggradation. The deposits consist of a few meters of rounded quartz-rich fluvial sand, silt, clay, rare rounded chert and quartzite pebbles, and rare limestone. The southward gradient of ancestral Grand Wash tributary sediments and interbedded Hualapai Limestone, implying earlier erosional lowering by an early Colorado River exiting westward through a bedrock canyon to the Temple Basin. Downfolded fluvial roundstone conglomerate (Figs. 8A and 8B) is interbedded with 4.4 Ma basalt of Sandy Point and has a minimum cosmogenic burial age of 4.8 ± 1.0–0.7 Ma. The base of the conglomerate lies at estimated 340 masl west of a reported fault and estimated 305 masl where submerged east of the fault, an estimated 220 ± 50 m inset below the projected top of Hualapai Limestone. Basal part of conglomerate locally includes 2 m boulders. Basalt cobbles are present below the basalt flow and are rare above the basalt flow. Roundstone conglomerate, 30 m thick, fills a nearby paleovalley. Nearby Colorado river deposits lie in angular unconformity across Hualapai Limestone at 300 masl and higher and locally lower. One deposit includes 5 m boulders. Colorado River–derived roundstone conglomerates occupy or occupied two perched and east-sloping (presumably tilted) paleovalleys (Spring Creek and Jumbo Pass). In the Spring Creek paleovalley, the roundstone conglomerate overlies rubble derived from Hualapai Limestone, into which the conglomerate is inset. Bouldery river conglomerate at 320 masl is unconformable on and inset at least 180 m into folded Hualapai Limestone (at Temple Bar). Intermittently exposed Colorado River conglomerate and lesser sandstone on the south flank of the river valley (Figs. 8C and 8D) occur as high as 700 masl (nearly as high as highest Hualapai Limestone; Fig. 4). The higher occurrences in places overlie slope rubble of blocks derived from the Hualapai Limestone, over sub-Hualapai mudstone layers. Highest occurrences are pebbly quartz-rich sandstone and typically exhibit a pronounced paleosol. On the assumption the roundstone conglomerates represent remnants of a continuous sequence, they are tentatively assigned to the Bullhead Alluvium. Intermittent exposures of Bullhead Alluvium roundstone gravel and cross-bedded sand include a continuous undeformed section, 100 m thick (Fig. 4), at 520 to 620 masl in E. Detrital Wash valley (Fig. 8E), and lower partial sections including a 10-m-thick section containing a layer of debris-flow blocks (derived from Hualapai Limestone and basalt) near 380 masl. Possibly downfaulted sections in SW Detrital Wash valley lie at intermediate elevations. Lower elevations (now under Lake Mead) lacked any cemented Colorado River deposits. Along the tributary Virgin River valley, locally faulted and tilted (1) fluvial pebbly sandstone at 350–400 masl underlies tephra correlated to 0.7–1.2 Ma, 25 km upstream of confluence with Colorado River (now in Lake Mead), and (2) fluvial roundstone conglomerate at 350–500 masl interfingers with the upper part of the Muddy Creek Formation 40 km upstream of the confluence. At Fisherman's Hole in the northern part of the Overton Arm of Lake Mead, roundstone conglomerate derived from the ancestral Virgin River dips basinward structurally.	Longwell (1936), Howard et al. (2000, 2003, 2008, 2010), Howard and Bohannon (2001), Faulds et al. (2001, 2008), Wallace et al. (2005), Beard et al. (2007), Lopez-Pierce et al. (2011), Matmon et al. (2012), Kimbrough et al. (2015).
Temple Basin	Hualapai Limestone, dated 6.0 Ma ~50 m below its top.		Longwell (1936), Laney (1979), Howard and Bohannon (2001), Spencer et al. (2001), Beard et al. (2007), this report.
Detrital Wash and more northern parts of Virgin Basin	Folded Hualapai Limestone and underlying Muddy Creek Formation unconformably underlie flat-lying Pliocene Colorado River deposits assigned to the Bullhead Alluvium.		Longwell (1936), Beard et al. (2007), Howard et al. (2010), this report.
	Along the Overton Arm of Lake Mead (northern Virgin Basin), mudstone of the Muddy Creek Formation interfingers with overlying roundstone gravel.		

(continued)

APPENDIX TABLE A1. STRATIGRAPHIC NOTES—PLIOCENE COLORADO RIVER SECTIONS (continued)

Area	Pre-Colorado River stratigraphy	Pliocene Colorado River stratigraphy	References
Boulder Basin	Limestone and gypsum at ~560 masl overlie 5.6 Ma tuff and may correlate to Bouse Formation; are apparently inset below Boulder Basin fill of locally derived Muddy Creek Formation and ca. 5.5 Ma basalt of Fortification Hill.	Old Colorado River deposits, >150 m thick inset deeply into preriver Boulder Basin fill, are assigned to the Bullhead Alluvium. The deposits (now mostly submerged below Lake Mead) are folded, faulted, and contain a tephra and at least one angular internal unconformity. Deposits consist of weakly indurated, alternating irregular beds of rounded gravel, cross-bedded sand, and silt; interfinger with or abut angular gravel and breccia of local origin; and contain <i>Camelops</i> bones and abundant silicified wood.	Longwell (1936), Howard and Bohannon (2001), Anderson (2003), Spencer et al. (2008).
Hoover Dam		Above Lake Mead, the Bullhead Alluvium consists of quartzose sandstone, pebbly sandstone, roundstone gravel, and silty claystone (as described in detail from Anderson [2003] in Appendix 1). Roundstone overlaid sandy conglomerate >28 m thick occupies a fluvially sculpted paleocanyon perched 270 m above Colorado River. Cosmogenic burial age calculated as 3.6 ± 0.5 Ma.	Howard et al. (2008), Matmon et al. (2012).
Cottonwood Valley	Basin-margin (shoreline?) deposits of the Bouse Formation as high as 550 masl. Bouse Formation laminated shale and nearby quartzose sands indicate that sediments including Colorado Plateau-derived sand had filled the basin at least to 400–420 masl.	Thick Bullhead Alluvium consists dominantly of cross-bedded sandstone, but roundstone conglomerate and at least one basal interval of 1 m boulders were observed. The formation is deeply inset into Bouse Formation.	Poulson and John (2003), House et al. (2005, 2008a, 2008b), House and Pearthree (2007), Pearthree and House (2015), this report.
Northern Mohave Valley	Bouse Formation mud at 370 masl in NW Mohave Valley overlies cross-bedded shore-facies sand containing volcanic pebbles derived (presumably via longshore currents) from >10 km upstream. Basin-margin (shoreline?) deposits of the Bouse Formation crop out as high as 550 masl.	Bullhead Alluvium, 250 m thick, dominated by quartzose sandstone and pebbly sandstone. Tephra correlated to 4.1 ± 0.5 Ma in interbedded piedmont alluvium near top of Bullhead Alluvium section. Identification of Nomiaki Tuff (3.3 Ma) in piedmont alluvium inset into Bullhead unit establishes minimum age of post-Bullhead degradation.	House et al. (2005, 2008b), Pearthree (2007), this report.
Southern Mohave Valley	Bouse Formation mudstones (locally containing detrital Cretaceous coccoliths) are exposed as high as 310 masl and interpreted at subsurface elevations as low as 88 masl; basin-margin limestone is exposed from 165 masl up to 440 m (definite) or 550 masl (probable).	Intermittent exposures of locally folded Bullhead Alluvium dominated by cross-bedded, locally pebbly sandstone, has conglomerate layers as thick as several meters, and silt and claystone (Figs. 8I–8K). Grades eastward into tributary arkosic material in Sacramento Wash (Fig. 8K). Where locally folded and faulted, angular unconformities separate fanning dips in section of roundstone conglomerate, diamictite, and claystone. Cosmogenic burial age $>4.1 \pm 0.3$ Ma. Exposed section has ~235 m projected thickness; is deeply inset below highest Bouse Formation mudstones. Possibly correlative subsurface fluvial gravels extend 50 m deeper below floodplain.	Smith (1970), Metzger and Loeltz (1973), Winterer (1975), House et al. (2005), Howard and Matmon (2007), Pearthree et al. (2009), Matmon et al. (2012), Howard et al. (2013), Spencer et al. (2013), this report.
Havas Lake Basin (Chemehuevi Valley)	Reconnoitered Bouse Formation basin-fill strata reach upper elevations >300 masl and Bouse Formation basin-margin carbonates span elevations from <140 m to 330 m.	Bullhead Alluvium is at 195 masl and recognized in the valley axis at 136–140 masl.	Carr (1991), this report.

(continued)

APPENDIX TABLE A1. STRATIGRAPHIC NOTES—PLIOCENE COLORADO RIVER SECTIONS (*continued*)

Area	Pre-Colorado River stratigraphy	Pliocene Colorado River stratigraphy	References
Parker Dam		Drilling in Aubrey Canyon in 1935 for Parker Dam placement indicated at least two bouldery intervals in an alluvial section up to 87 m thick inset into bedrock below the Colorado River. Apparent paleosols and cementation in the lower two thirds of the section suggest that the lower bouldery interval is the basal part of a Pliocene or lower Pleistocene fluvial section (Bullhead Alluvium?). An upper interval likely includes ~30 m of Holocene fluvial fill as suggested by the thickness of dated Holocene sections beneath the floodplain downstream near Blythe and upstream near Needles.	Berkey (1935b), Metzger et al. (1973), Howard et al. (2011), Howard and Maimon (2011).
Parker: northern parts of Blythe Basin including Vidal area, southern Whipple Mountains, Bouse Wash, and Mesquite Mountain.	Bouse Formation basin-fill facies assemblage interpreted as partly turbidites and grain-flow deposits derived from failure of a growing, more northerly delta front. Upper part of formation exhibits cross-bedding, and traction lineation interpreted as evidence of deltaic sedimentation in its transition upward into Colorado River sands and gravels. Sands in the transitional facies contain rounded hematite-coated single-crystal quartz grains identified as characteristic of provenance from the Colorado Plateau and indicative of Colorado River delivery. Bouse Formation interbedded unit (basin-fill facies) crops out to elevations <300 masl in the Blythe Basin. Sand facies of eolian and alluvial-fan materials mapped at higher elevations as part of the formation represents hillslope-derived debris (and windblown sands, which may include sands reworked upslope from a Bouse shoreline).	Gravels, including well-rounded quartzite, chert, and limestone pebbles derived from the Colorado Plateau, interfinger with fine-grained sediment in the Bouse Formation's upper part, and were interpreted as recording distributary channels in a Bouse Formation delta. Fluvial sand and roundstone gravel interpreted as Bullhead Alluvium extend to exposed elevations as high as >275 m east of the river and inset into the Bouse Formation. Drill logs in the Colorado River floodplain were interpreted to indicate absence of (Pliocene) Colorado River deposits where Holocene deposits directly overlie the Bouse Formation.	Metzger et al. (1973), Woodward-McNeill & Associates (1975), Fugro (1976), Dickey et al. (1980), Busing (1988, 1990, 1993), Carr (1991), Turak (2000), Spencer et al. (2008), this report.
Blythe area of central Blythe Basin	Bouse Formation, including thick interbedded unit containing fossil wood, and basal limestone drilled to 150 m below sea level.	Sand and gravel ("unit B"), interpreted as fluvial drilled to 55 m (possibly 100 m) below sea level, overlie the Bouse Formation; contain silicified wood. Cemented, cross-bedded, pebbly sandstone and conglomerate crop out to elevations as high as 250 m east of the Dome Rock Mountains, Arizona.	Metzger et al. (1973), Fugro (1976), Stone (2006), P. Stone (2008, oral commun.).
Palo Verde area in southern part of Blythe Basin	Bouse Formation interbedded unit was drilled from subsurface elevations near sea level to as much as >170 m deeper. Where drilled under Palo Verde Mesa, it was described as a lower clay-rich zone containing characteristic indigenous marinellike Bouse Formation fauna, and an upper sandy "transition zone," containing both indigenous and reworked Bouse Formation fauna. Under the floodplain, medium sand, ± pebbles and mud balls, dominates the upper 30 m of the Bouse Formation and may correlate with the "transition zone" under Palo Verde Mesa; if so, the transition zone dips basinward.	Under the Colorado River floodplain, riverlaid sand, roundstone gravel, and claystone ("unit B", or "QTrb") overlie "QTfa" and the Bouse Formation and its upper "transition zone." Where drilled beneath Palo Verde Mesa, a basinward-dipping section of angular conglomerate "QTfa" or "unit A" unconformably overlies the Bouse Formation and is in turn overlain unconformably by a thick section of sandy to gravelly "QTrb" fluvial sediments correlated to "unit B"; this fluvial section includes gently basinward-dipping clay layers, contains reworked Cretaceous foraminifera derived from the Mancos Shale on the Colorado Plateau, and can be divided into a lower subunit of silt and clay overlain unconformably by a sand-dominated subunit that attains a thickness of >80 m. Cross-bedded pebbly fluvial sandstone is mapped as high as 230 masl on the NW side of the Mule Mountains west of the river. Much but not all of the Colorado River section is magnetically reversed.	Fritts (1976), Lee and Bell (1976), Fugro (1976), Kukla and Updike (1976), Stone (1990, 2006).

(continued)

APPENDIX TABLE A1. STRATIGRAPHIC NOTES—PLIOCENE COLORADO RIVER SECTIONS (continued)

Area	Pre-Colorado River stratigraphy	Pliocene Colorado River stratigraphy	References
Southernmost part of Blythe Basin (Milpitas Wash, Cibola).	Extensive exposures of Bouse Formation limestone and some of the interbedded unit of Bouse Formation. 4.83 Ma Lawlor ash interbedded with Bouse limestone crops out at 306 masl here and at a similar elevation in distant Bristol basin far to the northwest.	Pliocene fluvial sediments were interpreted to be absent in the subsurface of the river's floodplain where upper Quaternary alluvium overlies the Bouse Formation at shallow depth.	Metzger et al. (1973), Fugro (1976), Roskowski et al. (2010), Spencer et al. (2013), Harvey (2014), Miller et al. (2014).
Yuma (Laguna Mountains, Chocolate Mountains, and Yuma and Bard Valleys).	Fine-grained sediments mapped as outcropping Bouse Formation alternatively can be interpreted as Colorado River sediments. Subsurface Bouse Formation identified from fauna, lithology, stratigraphic sequence (mudstones and conglomerate over a basal limestone), and geophysics.	Quartz-rich Colorado River sandstone, siltstone, and conglomerate mapped up to 225 masl (confirmed by us to 176 masl). Exposed section fines upward from sandstone and conglomerate to sand and silt. Subsurface sections of old Colorado River deposits under the Colorado River floodplain were logged as "wedge zone" and the overlying "coarse-gravel zone," and may be either inset into or conformable on Bouse Formation.	Olmsted (1972), Olmsted et al. (1973), Mattick et al. (1973), Nations et al. (2009), Spencer et al. (2013), this report.
Fortuna Basin	Subsurface fine-grained fossiliferous clastic strata that have been correlated to the Bouse Formation include an upper part described as a transition zone, as thick as 300 m, in which fossiliferous strata typical of Bouse Formation are interbedded with fluvial sands and gravels. The interbedding suggests a Colorado River deltaic environment. Marine and nonmarine sediments both underlie the Bouse Formation.	Thick alluvial sediments described as the "wedge zone" include both Colorado River and locally derived materials. Largely fine-grained in the subsurface. The overlying coarse gravel unit may include both Pliocene and younger components.	Olmsted et al. (1973), Mattick et al. (1973).
San Luis Basin	Subsurface fine-grained fossiliferous clastic strata that have been correlated to the Bouse Formation include an upper part described as a transition zone. Mollusk shells with seawater-like Sr isotopic compositions in the upper part of the Bouse Formation transition zone imply a marine delta environment.	Thick subsurface alluvial sediments described as the "wedge zone" include both Colorado River and locally derived materials. Largely fine-grained but at one well described as Colorado River gravels.	Olmsted et al. (1973), Eberly and Stanley (1978), Spencer and Patchett (1997), Pacheco et al. (2006).
Altar Basin	Miocene to Pliocene(?) marine shale, "sequence A", is 500–1000 m thick.	Marine "sequence B" consists of 600–2300 m of alternating mudstone and quartz-rich sandstone that downlaps onto the marine shale sequence A, and was interpreted as prodelta deposits of Colorado River origin. It contains reworked Cretaceous to Early Tertiary taxa interpreted as originating from the Colorado River. The overlying "Sequence C" sandstone, as much as 3460 m thick, includes gravel intervals 3–40 m thick, and at its top includes 200 m of exposed middle Pleistocene beds.	Pacheco et al. (2006).
Fish Creek–Vallecito Basin	Exposed upward transition from deeper marine to marine deltaic facies of Colorado Plateau–derived sediments in the upper part of the Imperial Group.	Fluvial Arroyo Diablo Formation records subaerial delta plain of Colorado River and tributary alluvium. Includes cross-bedded arenites, siltstones, mudstones, and fossiliferous gray limestone lenses.	Merriam and Bandy (1965), Winker and Kidwell (1986, 1996), Remeika and Fleming (1995), Dorsey et al. (2007, 2011), Nations et al. (2009).
Laguna Salada	Marine Imperial Formation (Group).	Colorado River–derived sediments assigned to the Imperial and Palm Spring Formations show stratigraphic complexities related to local tectonism.	Dorsey and Martín-Barajas (1999), Martín-Barajas et al. (2001).

Petrified wood is common in oxidized (“rusty”) intervals of cross-stratified sand and pea to pebble gravel. The petrified wood fragments are easily identified by their pristine appearance. One locale approximately 1 km south of Tyro Wash contains friable fragments of subfossil to partly petrified wood.

Moderately to strongly cemented bed-form elements are relatively common in the Bullhead sands, but in contrast, so are thick outcrops of very loosely consolidated sands.

A reference section that includes the basal boundary of the Bullhead Alluvium is designated on the southeastern outskirts of Laughlin, Nevada, where the formation overlies the Bouse Formation and sub-Bouse conglomerates, including “Pyramid gravel,” on an erosional unconformity (Fig. A1B; also see House et al., 2008b). The basal Bullhead Alluvium beds at this Laughlin reference section consist of cobble-boulder fluvial conglomerate enriched in coarse, locally derived clasts mixed with finer, far-traveled, nonlocal rounded cobbles and pebbles including conspicuous black chert pebbles (“Panda gravel” subunit of House et al., 2005). If deeper unexposed parts of the paleovalley exist, they could contain stratigraphically lower parts of the Bullhead Alluvium.

The top of the Bullhead Alluvium 5 km to the southeast in northern Mohave Valley, in the east part of the map, is indicated by the highest-elevation preserved remnants of rounded quartz-rich sand and nonlocal rounded pebbles on the valley flanks; these remnants cap an elevation range and apparent original paleovalley-fill formation thickness of 230 m (Fig. A1B). Angular debris deposits from younger, locally derived piedmont alluvial fans overlap and are inset into the formation.

Intervals of tabular beds of rounded conglomerate are as thick as 20 m (Figs. 8F and 8G; commonly weathered into roundstone lags in much younger colluvium). Trough and planar cross-beds in sandstone and conglomerate layers reach heights of 2 m. The sandstone and conglomerate of the formation typically are clast supported and well sorted to moderately well sorted, although some poorly sorted beds, several meters thick, contain sparse pebbles suspended in pale orange muddy sandstone matrix indicative of energetic flows. Mud balls (Fig. 8I) and subfossil wood are not uncommon, in one exposure including logs >1 m long. Orange iron-stained zones characteristically surround the fossil wood. Boulder conglomerate is locally present, enriched in locally derived subangular clasts mixed with nonlocal roundstone cobbles and pebbles (Fig. 8F). Pale orange mudstone occurs in places (Figs. 8I and 8K). More rare, light-gray claystone beds contain remains of turtle, lizard, rodent, fish, bivalves, ostracodes, and water reeds (R.E. Reynolds, 2008, written commun.; map unit Trbfl of Howard et al., 2013).

Clast assemblages include characteristic non-local well-rounded pebbles and lesser cobbles, especially chert, quartzite, and fossiliferous Paleozoic limestone. Sand fractions are rich in quartz, including well-rounded clear and hematite-coated grains, assemblages characterized as “C-suite” in the Salton Trough (Winker, 1987). Subrounded to subangular clasts of intermixed locally derived rock types such as gneiss, granite, and volcanic rocks can be as large as cobbles and boulders. Poorly sorted, locally derived angular conglomerate and sandstone layers derived from volcanic rocks, gneiss, and granite interfinger in the formation along the valley flanks. Internal angular unconformities are present in the Bullhead Alluvium in southern Mohave Valley (Lee, 1908; Metzger and Loeltz, 1973; Howard et al., 2013).

The assemblage of rounded nonlocal clasts, rounded quartz sand, and fluvial sedimentary structures demonstrates that the deposit largely consists of material transported and deposited from distant sources by the ancestral Colorado River, with lesser intermixed locally derived debris.

The underlying Bouse Formation in Cottonwood Valley overlies the “Lost Cabin beds” and a contained tephra bed geochemically correlated to the tuff of Wolverine Creek, ca. 5.6 Ma (House et al., 2008a, 2008b). A stratigraphically low part of the Bullhead Alluvium yielded a minimum cosmogenic-isotope burial age of 3.6 ± 0.5 Ma (Matmon et al., 2012). A tephra bed within locally derived alluvial-fan deposits interbedded near the top of the Bullhead Alluvium was assigned an age of 4.1 ± 0.5 Ma based on geochemical correlation to a “lower Nomlaki tephra” (House et al., 2008b), now called tuff of Artists Drive (Knott et al., 2008). Another tephra bed correlated to the 3.3 Ma Nomlaki Tuff is inset 50 m below the highest beds of the Bullhead Alluvium and constrains the Bullhead Formation to be older. Therefore, the Bullhead Alluvium is Pliocene, younger than the post-5.6 Ma Bouse Formation and older than 3.3 Ma. As explained in text, we estimate its age spans from ca. 4.5 Ma to ca. 3.5 Ma.

Boulder Basin

Lake Mead now mostly drowns a folded and faulted section of Colorado River deposits >150 m thick in Boulder Basin that was described by Longwell (1936; Figs. 3 and 4). The section consists of variably cemented Colorado River alluvium, locally derived interbeds, and a (now-drowned) tuff bed (Longwell, 1936; Anderson, 2003). Longwell (1946) found a Pleistocene or Pliocene camel bone in the section. We assign this section to the Bullhead Alluvium. The section is folded and faulted and contains internal unconformities. The thick, deeply inset section cropped out down to near river level before Lake Mead filled (Fig. 4). This elevation is 575 m lower than a possible level of Upper Miocene preriver basin fill (Longwell, 1936) and 435 m lower than ca. 5.6 Ma lacustrine gypsum and limestone interpreted by Spencer et al. (2013) as deposited in a Bouse Formation lake on the flank of the basin.

The upper part of the Bullhead Alluvium exposed above Lake Mead consists largely of

“fluvial sandstone, pebbly sandstone, and roundstone gravel; includes some moderately lithified thin-bedded silty claystone. Sand is mostly quartzose, moderately well sorted, fine to medium grained, very indistinctly to very distinctly bedded, flat-bedded to complexly cross-bedded. Cut-and-fill channel deposits are common. Some massive beds contain very sparse to common suspended pebbles and, locally, suspended cobbles, suggesting they are, in

part at least, high-energy flood deposits. Gravel beds are mostly sandy and are clast supported, consisting of strongly bimodal assemblages of rounded and angular clasts in highly variable proportions, suggesting complex intercalation of locally derived and far-traveled detritus, especially near the contact with [alluvium locally derived from side washes]..... Rounded pebbles and cobbles of...quartzite and...chert are common. Silty claystone is thin-bedded, rhythmically flat-bedded, and more varied in color than the sandy beds” (Anderson, 2003, p. 2).

Detrital Valley

High exposures of Colorado River deposits (fig. 34 of House et al., 2005) include a well-exposed section, 100 m thick, on the east valley margin consisting of 45 m of sandstone and minor conglomerate overlying 55 m of interbedded sandstone and imbricated cobble-pebble conglomerate, including a 4 m interval of cobbles and small boulders and a local 8 m bed of poorly sorted, subrounded locally derived debris. Consistently southward-directed pebble imbrication and cross-bedding in the Colorado River deposits are consistent with aggradation advancing southward as tongues of the braided river backfilled this transverse basin. Colorado River deposits exposed at lower elevations close to Lake Mead include a 10-m-thick remnant of sandy roundstone cobble conglomerate containing a debris-flow rubble bed of 1–3 m blocks of locally derived Hualapai Limestone and basalt.

Lake Havasu Basin

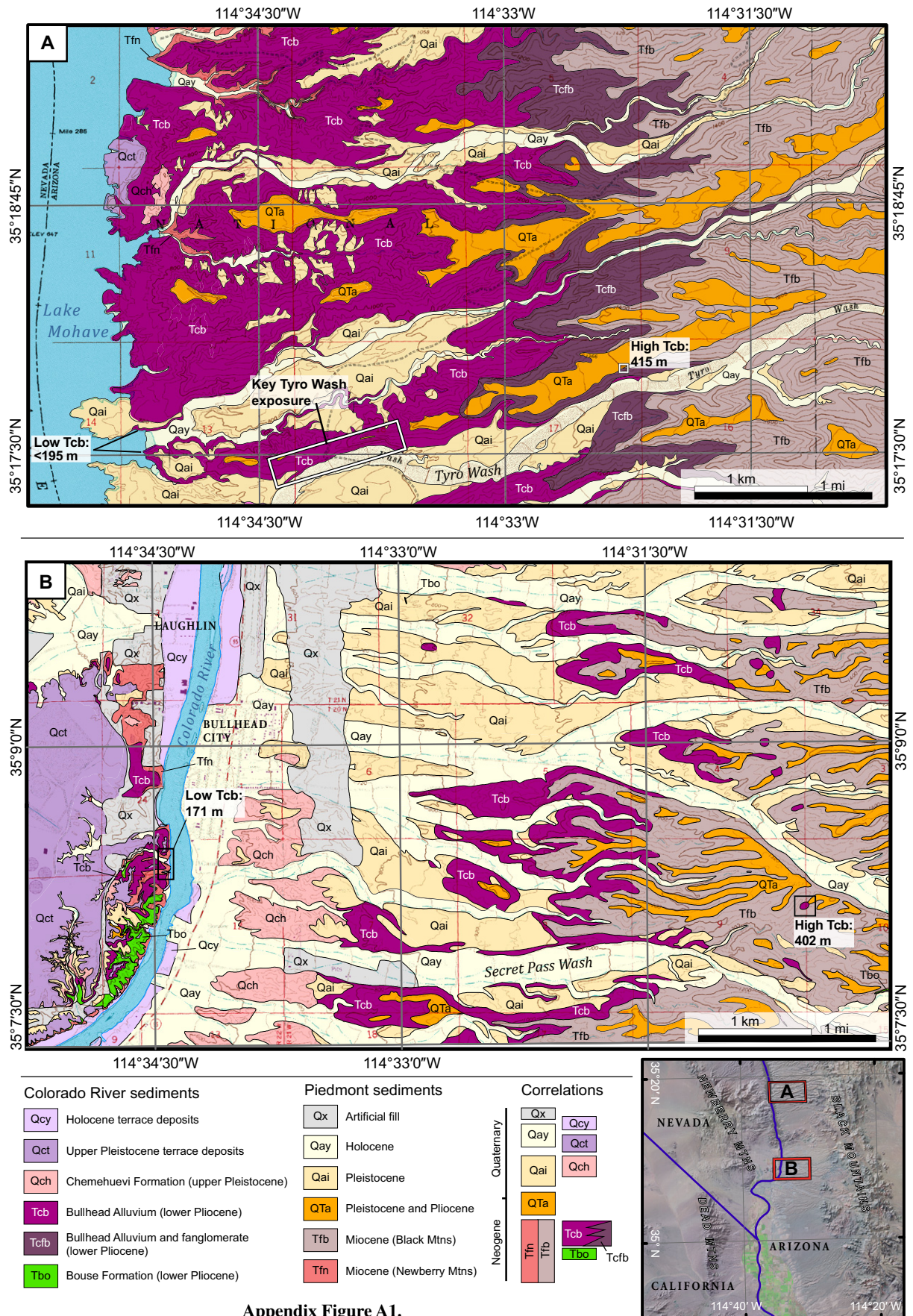
Lake Havasu Basin (Fig. 2) exposes Bullhead Alluvium sandstone and conglomerate, locally bearing petrified wood, from the shores of Lake Havasu to elevations 102 m higher in Chemehuevi Valley. Angular, locally derived tributary gravel up to 6 m thick locally separates the Bullhead and Bouse Formations, and younger tributary gravel truncates the top of the highest Bullhead Alluvium found to date.

Blythe Basin

Only some of the abundant Colorado River deposits exposed in the Blythe Basin (Parker-Blythe-Cibola area) may be Bullhead Alluvium. In the Parker area, we assign to the Bullhead Alluvium a sequence of cemented roundstone conglomerate and sandstone at Headgate Dam near the level of the modern floodplain; they overlie the Bouse Formation on an erosional surface with 6 m of vertical relief. At 113 masl, they are 180 m lower than Bouse Formation and interbedded Colorado River deposits a few kilometers away. Elsewhere in the Blythe Basin, new geologic mapping will be required to fully distinguish Bullhead Alluvium from fluviodeltaic deposits that conformably overlie the Bouse Formation (Buisson, 1990).

Appendix Figure A1. Geologic maps of type and reference sections of Bullhead Alluvium (located in Fig. 2). (A) Geologic map of proposed stratotype Bullhead Alluvium in the Tyro Wash area, Arizona. Rectangle outlines an area of easily accessible typical exposures. Map is modified from House et al. (2005a). (B) Geologic map of reference section for the basal Bullhead Alluvium (area near box west of the river) near Laughlin, Nevada, where it rests with erosional unconformity on Bouse Formation limestone and Miocene conglomerate (House et al., 2005). Scattered exposures on the Bullhead City, Arizona piedmont (east of the river) occur up to the apparent top of the formation at the highest exposures at 402 m above sea level. Map is modified from Faulds et al. (2003).

Pliocene aggradation on the lower Colorado River



APPENDIX 2. SECTIONS TENTATIVELY CORRELATED TO THE BULLHEAD ALLUVIUM

Here, we describe some sections that are tentatively correlated to the Bullhead Alluvium. Additional information is given in Table A1.

Hoover Dam Potholes

Overlooking Hoover Dam, two small remnants of cemented Colorado River alluvial deposits, 28 m thick, filling potholes and a river-sculpted and polished paleogorge are perched 270 m above the historic Colorado River (Matmon et al., 2012). The cosmogenic burial age of 3.6 ± 0.5 Ma (Matmon et al., 2012) of this alluvium is consistent with correlation of this section to the Bullhead Alluvium, although the possibility that the sculpturing and potholes record pre-Bullhead tool-driven erosion of a divide cannot be disproven. If the partial section correlates to the Bullhead Alluvium, the high elevation may indicate a stage of temporary incision and re-aggradation near the high-stand culmination of the Bullhead aggradation.

Temple Basin

Temple Basin, like adjacent Detrital Valley, exposes a series of fragmentary sections of Colorado River deposits of conglomerate and sandstone over a 300+ m range of elevations inset into the Hualapai Limestone (Figs. 8C and 8D; Beard et al., 2007; Howard et al., 2008). The scattered exposures are inset from 5 m to at least 180–200 m into folded Hualapai Limestone. The thickest remnants expose about 20 m of continuous section, including southward-directed pebble imbrication. Quartz-rich sandstone capped by a paleosol at 700 masl forms the highest remnants, near the highest Hualapai Limestone. At the shores of Lake Mead, 335 m lower, remnants of pebble-cobble roundstone conglomerate in a calcareous sand matrix include subrounded 1–2 m boulders of locally derived gneiss, granite, conglomerate, and limestone; the remnants unconformably overlie folded Miocene conglomerate and limestone on an irregular erosion surface, locally wedging 7 m under a bedding slab of the 20°-dipping conglomerate substrate. Incomplete sections of the roundstone alluvium remnants and structural dips toward the basin axis in the underlying Hualapai Limestone render uncertain the composite thickness of the Colorado River deposits and whether they represent more than one sequence. The positions of the highest exposures nearly as high as the older Hualapai Limestone open the possibility that they were deposited during pre-Bullhead downcutting. These highest Colorado River deposits commonly are capped by a very well-developed calcareous paleosol.

Greggs Basin

Greggs Basin exposes a faulted 60-m-thick section of Colorado River deposits of sandy roundstone conglomerate (Figs. 8A and 8B) and the interlayered 4.4 Ma basalt of Sandy Point (Faulds et al., 2001). This section lies unconformably on sub-Hualapai Limestone Miocene conglomerate and is inset an estimated 220 ± 50 m below the projected Hualapai Limestone (Fig. 4; Matmon et al., 2012). Part of the Sandy Point section of alluvium and basalt is downfaulted and submerged below Lake Mead, and the 60 m thickness is reconstructed based on Longwell's (1936) pre-Lake Mead observations. The presence of other partial sections of Colorado River deposits at similar elevations

in Greggs Basin is consistent with the Sandy Point section as a record of the Bullhead aggradation rather than aggradation localized just in the hanging wall of an active Wheeler fault. The other sections include roundstone conglomerate capping deformed Hualapai Limestone and filling a narrow paleovalley (Longwell, 1936; Wallace et al., 2005; Brady et al., 2002; Howard et al., 2003, 2008). Apparent depths of inset (200–240 m) are like those in Temple Basin. Additional Colorado River conglomeratic deposits occupy perched, east-downfolded paleovalleys inset 90 m below the top of the Hualapai Limestone and bridging between the two basins (Howard et al., 2003). These paleovalley fills, up to 35 m thick, were inferred to record Colorado River aggradation in Greggs Basin (Howard et al., 2008), although their lesser inset (100–125 m) below Hualapai Limestone alternatively could be interpreted to record the result of intermittent back-filling during pre-Bullhead stages of downcutting. If they are part of the same sequence as at Sandy Point and in the Temple Basin, the geomorphic position of the gravels, as reconstructed for younger downfolding, implies the Colorado River sequence in Greggs and Temple Basins originally could have been ≥ 130 m thick. The geomorphic and stratigraphic positions and possible reconstructed thickness of the sections in Greggs Basin lead us to correlate them tentatively to the Bullhead Alluvium.

Grand Wash Trough

Eastward across the Wheeler fault in the Grand Wash Trough, near the mouth of the Grand Canyon, cemented Colorado River gravels were mapped ~95–245 m above the historic Colorado River and inset ~320–460 m below nearby uppermost Hualapai Limestone (Lucchitta, 1966). These gravels show less of the distinctive quartz-rich thermal-infrared signal on Master remote-sensing imagery (Hook et al., 2005; Howard et al., 2008) than is typical of most Colorado River deposits.

Parker Dam and Other Dam Sites

An 80-m-thick canyon fill of Colorado River alluvial deposits drilled over bedrock at Parker Dam site included fine sediment in the upper part, which we infer to be like dated Holocene deposits that extend at least 30 m below the floodplain surface in Mohave and Blythe Basins (Metzger et al., 1973; Howard et al., 2011). We suspect that partly cemented and bouldery lower parts of the section may correlate to the Bullhead Alluvium (Berkey, 1935b; Howard and Malmon, 2011).

Alluvium also filled bedrock canyons beneath the historic Colorado River at Davis Dam (>60 m thick, between Cottonwood and Mohave Valleys), Hoover Dam (38 m), and in Boulder Canyon between Detrital Valley and Boulder Basins (48 m; LaRue, 1925; Berkey, 1935a, 1935b; USBR, 1935; Longwell, 1936). Whether or not any correlates to the Bullhead Alluvium, the basal elevations limit the maximum possible depth of Bullhead profile I.

Blythe Basin

Our reconnaissance in Blythe Basin suggests that much of unit B (Metzger et al., 1973) and the equivalent unit QTrb of Fugro (1976; Lee and Bell, 1975; Stone, 1990, 2006) correlate with the Bullhead Alluvium. Detailed mapping will be required to separate out subadjacent fluviodeltaic Colorado River deposits that are interbedded with the top of the underlying

Bouse Formation (Buising, 1990; Fig. 5). Quartz-rich sandstone and roundstone conglomerate packages that crop out in the Blythe area at elevations from 87 masl at the edge of the floodplain to a paleovalley fill 140 m higher in elevation in the Mule Mountains (Stone, 2006) likely correlate to the Bullhead Alluvium.

Probable Bullhead Alluvium also crops out along the western front of the northern Trigo Mountains near Cibola, Arizona, with characteristic rounded chert-clast-rich pea gravel; small rounded nonlocal cobbles; and cross-bedded fluvial sandstone. Exposed thickness in this area is approximately 40 m. The highest outcrops identified to date reach 225 masl, and this probable Bullhead Alluvium is truncated at its top by tributary gravel that contains reworked, rounded, nonlocal roundstone gravels, rare clay balls, and reworked Bouse Formation tufa.

Metzger et al. (1973) identified thick subsurface sections as unit B under the Colorado River floodplain from well cuttings to depths at least 62 mbsl overlying the Bouse Formation (Metzger et al., 1973; Fig. 4). Pebble assemblages identified in unit B were significantly different from those of more rare pebbles in the Bouse Formation, and unit B sands were distinguishable from sands in the Bouse Formation (Metzger et al., 1973, p. 16, 19). The unit B sections commonly contain silicified wood and clay balls. The sections include silty and clayey sand coarsening upward to mostly sand (5 km west of Palo Verde; Fugro, 1976; Fig. 4). Like the Bullhead Alluvium upstream, the Colorado River deposits occur at lower elevations than some Bouse Formation exposed higher on the valley flanks, into which it was interpreted to be inset by Metzger et al. (1973) and Fugro, Inc. (1976). A further distinction is faunal. An estuarine-like indigenous fauna including many foraminifers is common in the Bouse Formation in the Blythe Basin, including in a sandy and pebbly interval near the top of the Bouse Formation (log of test well LCRP 27 in Metzger et al., 1973; Smith, 1970; Winterer, 1975; Fritts, 1976; McDougall, 2008; McDougall and Martinez, 2014). In contrast, the subsurface unit QTrb (equivalent to Colorado River deposits of unit B) overlying the Bouse interval instead contains detrital Cretaceous foraminifera and *Inoceramus* clam fragments (Fritts, 1976). Drill logs provide little descriptive detail to distinguish the sandy unit B subsurface sections as fluvial rather than subaqueous density-flow deposits. A subsurface lens, 6–36 m thick, of angular locally derived gravel sandwiched (near modern sea level) between the Bouse Formation and overlying QTrb unit near Palo Verde (Fugro, 1976; Fig. 4) resembles thinner alluvial-fan gravel between the Bouse and Bullhead Formations in the Lake Havasu Basin. Angular gravels in this position are consistent with alluvial fans deposited after incision of the Bouse Formation and heralding the onset of Bullhead aggradation (cf. Metzger et al., 1973).

Yuma Area Exposures

The Yuma area exposes quartzose sandstone and roundstone conglomerate typical of Bullhead Alluvium over an ~100 m range of elevations up to at least 176 masl on both sides of the river valley (Figs. 3, 4, 8L, and 8M; Olmsted et al., 1973, their figs. 19 and 20). As reported and mapped by Olmsted et al. (1973), Colorado River gravels reach another 54 m higher in elevation, although we were unable to confirm it. Lithology, thickness, fossil wood (Nations et al., 2011), and elevation of the highest exposures along the downstream projection of the longitudinal profile (Fig. 3) all suggest to us that this section correlates to

the Bullhead Alluvium. However, a clear inset relation into the Bouse Formation is uncertain, given that correlation is disputed for the only exposed rocks attributed to the Bouse Formation (Olmsted, 1972; Olmsted et al., 1973; Nations et al., 2009; Spencer et al., 2013). Nations et al. (2009) studied the exposed Pliocene Colorado River alluvial deposits in the Yuma area for clast content, paleocurrent directions, and abundant silicified wood, and they correlated the assemblage of petrified wood to a similar assemblage in the Arroyo Diablo Formation of the Fish Creek–Vallecito Basin. Olmsted et al. (1973) inferred a complex aggradation history for the alluvium as reflected in multiple internal unconformities; we infer that fluvial channeling may account for at least some of the erosional breaks (Henshaw, 1942).

APPENDIX 3. SEQUENCES IN AND NEAR THE SALTON TROUGH

Fortuna, San Luis, and Altar Basins

Abundant subsurface information is available for these sedimentary basins. The Fortuna Basin extends and deepens southeastward from the basin's head at Yuma. A buried bedrock ridge and the Algodones fault separate the Fortuna Basin from the San Luis Basin to the southwest. The San Luis Basin in turn merges southward with the Altar Basin. The Algodones–Altar fault zone is on strike with the dextral San Andreas fault and inferred to be a major part of the Pliocene plate boundary.

Drill logs in the Fortuna and San Luis Basins typically identify a thick sequence of alluvium, designated the “wedge zone” by Olmsted et al. (1973) for its overall geometry. It lies beneath Quaternary fine-grained sediments and a complex zone of coarse gravel bodies. Similar subsurface stratigraphic relations were recognized in the adjacent San Luis Basin (Olmsted et al., 1973). The wedge zone consists largely of sand and silt but includes gravels and rarer clay intervals. Drill logs and pebble counts show that Colorado River sediment dominates the wedge zone, but some angular locally derived debris is also present (Olmsted et al., 1973; Eberly and Stanley, 1978).

The wedge zone overlies a fossiliferous transition zone of interbedded marine and fluvial deltaic beds that was designated as the upper part of the Bouse Formation (Olmsted et al., 1973; Mattick et al., 1973; Eberly and Stanley, 1978). The “Bouse Formation” in this section generally resembles the Bouse Formation in the Blythe Basin in stratigraphic position, fauna, logged geophysical profile, and the upward transition into deltaic facies, although all but a few sections lack a basal limestone, and some faunal assemblages are more typically marine (Olmsted et al., 1973; Mattick et al., 1973; Smith, 1970; McDougall, 2008). Lithology and stratigraphy suggest to us that the wedge zone and part of the overlying coarse gravel likely correlate to the Bullhead Alluvium (Figs. 6 and 7). Its basal contact on the transition zone may be conformable. The wedge zone reaches thicknesses of 548 m in the Fortuna Basin and >531 m in the San Luis Basin (Olmsted et al., 1973; Mattick et al., 1973; Eberly and Stanley, 1978).

Where imaged seismically, thick undated plane-bedded alluvial sections of sand, conglomerate, and silt in the San Luis and Altar Basins overlie thick, downlapping deltaic marine sequences (Pacheco et al., 2006). The very thick (Fig. 7) fluvial “sequence C” in the Altar Basin, characterized from drill-hole information, extends up to exposed middle Pleistocene deposits containing an Irvingtonian vertebrate fauna.

Fish Creek–Vallecito Basin

A thick exposed Pliocene section has been tightly calibrated for age and thickness based on careful geologic mapping, closely spaced paleomagnetic sampling, and constraints from biostratigraphy low in the section and dated tuffs high in the section (Dorsey et al., 2011). The lowest appearance of Colorado River debris in the section is at a horizon correlated to 5.3 Ma in the Wind Caves Member of the Latrania Formation of the marine Imperial Group. Following Dorsey et al. (2011), we use the stratigraphic nomenclature of Winker and Kidwell (1996), as slightly modified by later authors. The overlying Deguynos Formation begins with the Mud Hills Member, consisting of a marine claystone (ca. 5.1–4.9 Ma) and marine rhythmites (ca. 4.9–4.5 Ma). The Yuha Member (ca. 4.5–4.35 Ma) and Camels Head Member (ca. 4.35–4.25 Ma) of the Deguynos Formation consist of shallow-marine Colorado River delta deposits. The transition to nonmarine deposits occurs at ca. 4.25 Ma (within the Cochiti magnetochron, 4.19–4.30 Ma) at the base of the Arroyo Diablo Formation within the nonmarine Palm Spring Group. The Arroyo Diablo and interfingering Olla Formation, together 2500 m thick, record continued fluvial deposition until younger than 3.0 Ma.

The alluvial Arroyo Diablo Formation in the Palm Spring Group conformably overlies Pliocene Colorado River–derived deposits in the marine Imperial Group. The Arroyo Diablo Formation consists of medium to fine, C-suite sand and abundant interfingering angular locally derived debris (Fig. 8N); it contains paleosols and rare Colorado River roundstone pebble gravels (Winker and Kidwell, 1986; Kerr and Kidwell, 1991; Dorsey et al., 2011). The Arroyo Diablo Formation extends upward to <3 Ma (Dorsey et al., 2011). The formation represents the delta plain of the Colorado River and must represent in part a distal equivalent of the Bullhead Alluvium.

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