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Redefining the age of the lower Colorado River, southwestern United States

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ABSTRACT

Sanidine dating and magnetostratigraphy constrain the timing of integration of the lower Colorado River (southwestern United States and northern Mexico) with the evolving Gulf of California. The Colorado River arrived at Cottonwood Valley (Nevada and Arizona) after 5.24 Ma (during or after the Thvera subchron). The river reached the proto–Gulf of California once between 4.80 and 4.63 Ma (during the C3n.2r subchron), not at 5.3 Ma *and* 5.0 Ma as previously proposed. Duplication of section across newly identified strands of the Earthquake Valley fault zone (California) probably explains the discrepancy. The data also imply the start of focused plate motion and basin development in the Salton Trough (California) at 6–6.5 Ma and relative tectonic stability of the southernmost part of the lower Colorado River corridor after its integration. After integration, the Colorado River quickly incised through sediment-filled basins and divides between them as it also likely excavated Grand Canyon (Arizona). The liberated sediment from throughout the system led to deposition of hundreds of meters of Bullhead Alluvium downstream of Grand Canyon after 4.6 Ma as the river adjusted to its lower base level.

INTRODUCTION

Our study resolves two controversies about the lower Colorado River (southwestern United States and northern Mexico)—its age and how it integrated from the Colorado Plateau to the Gulf of California (GOC). The lower Colorado River corridor below Grand Canyon provides the needed sedimentary record to resolve these controversies because the Bouse Formation records the arrival of the lower Colorado River in a series of basins that stretch from the Colorado Plateau to the GOC. This heterolithic unit consists of basal carbonate and siliciclastic deposits (Metzger, 1968), including Colorado River sand (Kimbrough et al., 2015). Although this unit is widely interpreted as lacustrine in the upper basins, McDougall and Martínez (2014) and Dorsey et al. (2018) argued that fossils in the basal carbonate of the Bouse Formation show that the Colorado River met a marine or estuarine embayment of the proto–GOC in the southern Blythe Basin that started forming at ca. 6 Ma. Others have argued that the Bouse Formation is entirely lacustrine (Spencer et al., 2013; Pearthree and House, 2014; Bright et al., 2016). Field evidence records the catastrophic breaching of at least one divide in the upper basin (House et al., 2008). This supports a model of downstream-directed filling and spilling as Colorado River water and detritus passed sequentially through overflowing basins (House et al., 2008; Spencer et al., 2013; Pearthree and House, 2014). We test competing models with improved and existing geochronologic constraints on the first arrival of the Colorado River to a series of sites along the lower Colorado River corridor: between the Lake Mead area (Nevada and Arizona, USA) and the GOC (Fig. 1).

Prior geochronologic work has already constrained the arrival of the Colorado River along this route (Fig. 1). In the Lake Mead area, the Colorado River's arrival is bracketed between 6.0 and 4.7 Ma (Fig. 1B). In Cottonwood and Mohave Valleys, its arrival is bracketed between 5.7 and ca. 4.1 Ma (Fig. 1C). The 5.0–4.9 Ma Lawlor Tuff is interbedded in some of the highest Bouse Formation outcrops in Blythe Basin (California and Arizona; Fig. 1D), dating the time the basin filled. In the Fish Creek–Vallecito Basin (California; Fig. 1E), which has been translated >200 km to the northwest along the San Andreas fault system, first-arriving Colorado River sediment is preserved in the marine Wind Caves member of the Latrania formation of the Imperial group (officially named the Latrania Member of the Imperial Formation; Hanna, 1926) (Winker and Kidwell, 1996). Magnetostratigraphy calibrated by 2.6 Ma ashes high in the >5-km-thick section was used to infer that Colorado River sediment first arrived at the GOC at 5.3 Ma (Dorsey et al., 2011). This is puzzling because upstream, Bouse carbonate in the Blythe Basin was still being deposited at 5.0–4.9 Ma (Fig. 1D). Dorsey et al. (2018) explained this discrepancy with a multi-stage model that involved a ca. 6 Ma marine incursion into the Blythe Basin, Colorado River integration to the GOC in the Pliocene as early as 5.3 Ma, and marine reflooding of the Blythe Basin at ca. 5.0 Ma followed by reintegration of the Colorado River to the GOC and regional uplift.

We present new geochronologic data that support a simpler integration model of entirely downstream-directed fill-and-spill processes that culminated between 4.80 Ma and 4.63 Ma with the birth of a continental-scale river, which had a drainage basin comparable to the modern (Kimbrough et al., 2015). The new results also suggest that the Colorado River corridor aggraded rapidly after integration to the GOC, that little to no post-integration uplift of the

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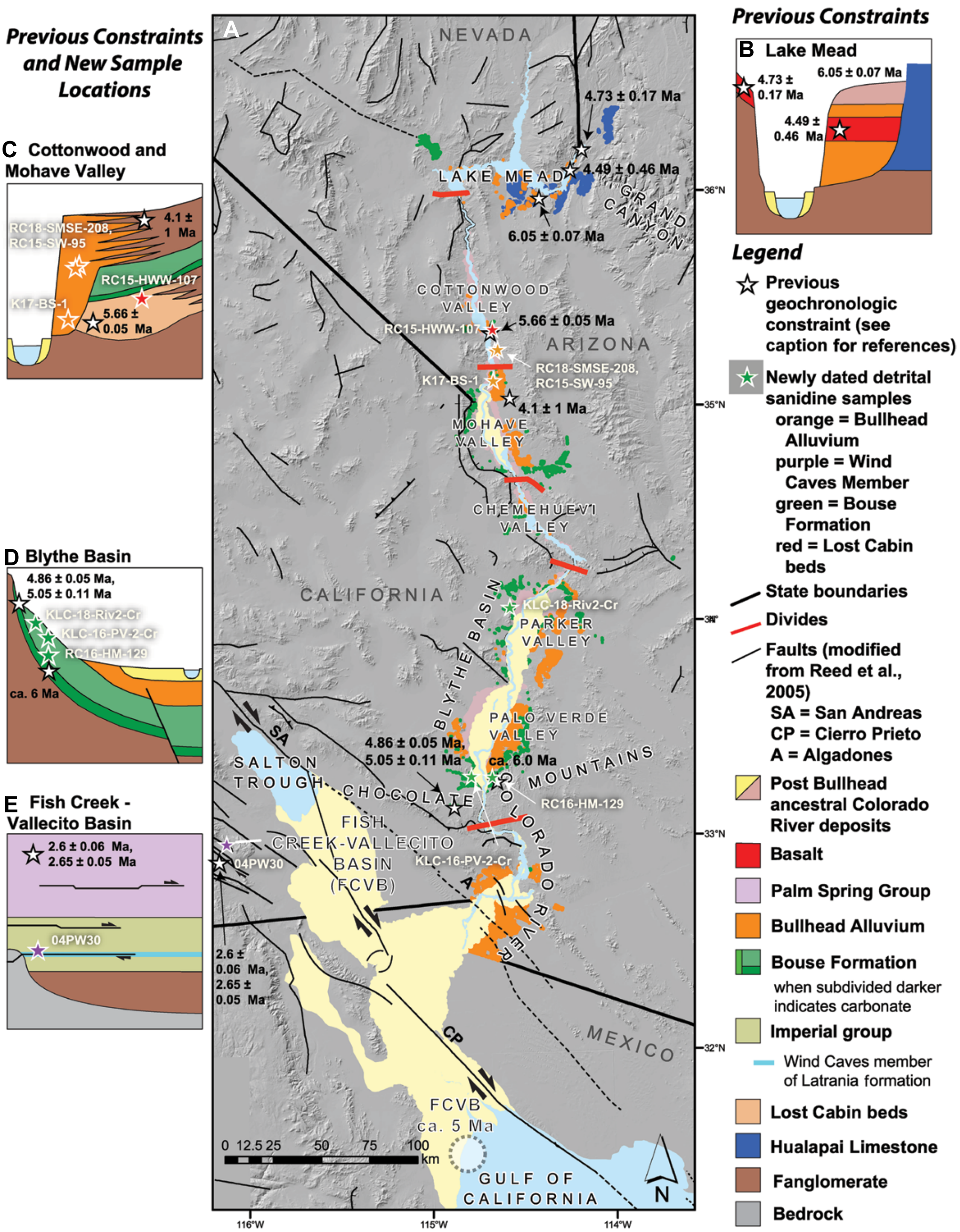

Figure 1. (A) Map of the lower Colorado River corridor (after Crow et al., 2018). (B–E) Schematic diagrams showing relations between constraints on timing of Colorado River arrival: to the Lake Mead area (B), where 6.0 Ma ash in Hualapai Limestone (Spencer et al., 2001) pre-dates the arrival of the river, and 4.5 Ma Sandy Point basalt flow (Faulds et al., 2016) and 4.7 Ma basalt flow in the Grand Wash (Crow et al., 2019) post-date it; to Cottonwood Valley (C), where 5.7 Ma ash pre-dates arrival of the river, and 4.1 Ma ash post-dates it (House et al., 2008); to Blythe Basin (D), where paleontology suggests the basal Bouse Formation carbonates are 6.0 Ma toward the center of the basin (McDougall and Martinez, 2014) and geochronology suggests carbonates are 5.0–4.9 Ma on the flanks at the highest levels (Sarna-Wojcicki et al., 2011; Harvey, 2014); and to the Fish-Creek–Vallecito Basin (E), where 2.6 Ma ashes higher in the section are tied to first-arriving Colorado River sand by magnetostratigraphy (Dorsey et al., 2007, 2011). Earthquake Valley fault zone is shown schematically.

Blythe Basin occurred, and that the oldest syntectonic basins in the Salton Trough may only be 6–6.5 Ma.

METHODS

We present new Ar/Ar dates from a tephra and detrital sanidine (DS) from sand samples, combined with magnetostratigraphy, in deposits that (1) immediately pre-date the arrival of the Colorado River (Lost Cabin beds), and (2) record the initial development of the Colorado River (Bouse Formation, Wind Caves member, and Bullhead Alluvium). Single-crystal Ar/Ar dating of sanidine was primarily conducted at the New Mexico Geochronology Research Laboratory (Socorro, New Mexico, USA). Argon was extracted by laser fusion, and isotopes were measured using an ARGUS VI mass spectrometer (MS). One sample was also dated at the U.S. Geological Survey (USGS) laboratory in Menlo Park (California, USA) using similar methods on a Nu Instruments Noblesse MS. K-feldspar was concentrated by standard methods, and sanidine grains were hand-picked from the bulk K-feldspar population based on optical properties while immersed in oil of wintergreen. All new and previously published Ar/Ar ages (Table S1 in the Supplemental Material[1]) are reported based on the same decay constant (Min et al., 2000) and equivalent monitor

[1]Supplemental Material. Additional details on methods, summary of previous Ar/Ar dating relevant to the timing of Colorado River integration, sample locations, and full analytical results. Please visit https://doi.org/10.1130/GEOL.S.13530698 to access the supplemental material, and contact editing@geosociety.org with any questions.

ages (Kuiper et al., 2008); analytical errors are reported to 2σ. Our approach involved deriving maximum depositional ages (MDAs) from sediments and tying those to new or published magnetostratigraphy and the global polarity time scale (GPTS) of Ogg (2012) and Channell et al. (2020). For new paleomagnetic work, oriented sediment samples were analyzed at the University of Oklahoma (Norman, Oklahoma, USA) using a 2G Enterprises cryogenic magnetometer with DC squids, and AF demagnetizer. Thermal work was completed using ASC Scientific's thermal demagnetizing oven. See the Supplemental Material for expanded methodology.

NEW AGE CONSTRAINTS AND IMPLICATIONS

We present dating results from >1300 single grains from eight samples. The youngest population of dates from a DS sample as defined by the mean square of weighted deviates (MSWD) value is chosen to represent the MDA, and the assigned age and error are given by the inverse variance weighted mean. These ages are presented in Figure 2, and all data are given in Tables S2, S3, and S4. Note that in one case the MSWD is slightly elevated (lower Bullhead, MSWD = 5.41), but this could be explained by high flux gradients during irradiation where individual grains do not receive the exact same neutron flux. We also present magnetostratigraphy across a key ash bed in the upper Lost Cabin beds. Age constraints are organized geographically from upstream to downstream.

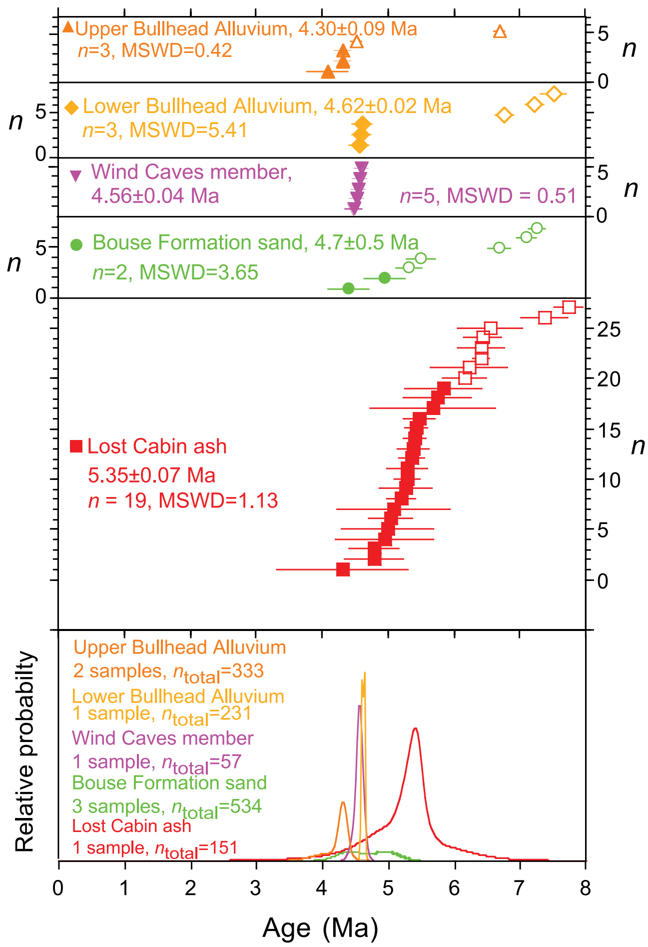

Figure 2. Ar/Ar sanidine geochronology results for grains with dates between 0 and 8 Ma. Solid symbols indicate analyses used to define weighted mean ages, and open symbols show analyses excluded from calculation. *N* represents the number of grains for each unit that fall between 0 and 8 Ma, whereas *n* is the number of grains defining weighted mean age. N_{total} is total number of grains dated from each unit. Weighted mean ages record the maximum depositional age of sedimentary units or time of tephra deposition. All age uncertainties are reported at 2σ. MSWD—mean square of weighted deviates.

Cottonwood and Mohave Valleys

New dating of the Lost Cabin beds in Cottonwood Valley more tightly constrains the age of the overlying Bouse Formation. The Lost Cabin beds are a 60 m-thick section of fine-grained axial-basin deposits that accumulated in Cottonwood Valley prior to the arrival of the Colorado River (House et al., 2020). The deposits contain multiple ashes, one of which was correlated to the 5.7 Ma Wolverine Creek eruption from the Heise eruptive center in Idaho (House et al., 2008). We conducted Ar/Ar dating on a stratigraphically higher ash (sample RC15-HWW-107) that is ~15 m below the Bouse Formation. The results confirmed field observations that the centimeter-thick ash had been reworked because the sanidines are dominantly (>80%) middle Miocene, presumably derived from tuffs exposed to the east. However, a population of 19 grains gave a much younger age of 5.35 ± 0.07 Ma (Fig. 2). Paleomagnetic analysis of the ash and surrounding sediments indicates the presence of a reverse-to-normal polarity transition directly above the ash (Schwing, 2019; Supplemental Material), which we assign as the base of the 5.24–5.0 Ma Thvera subchron. Therefore, the Bouse Formation in Cottonwood Valley is younger than 5.24 Ma.

Three DS grains from near the base of the Bullhead Alluvium, which is inset into the Bouse Formation, yielded an MDA of 4.62 ± 0.02 Ma (Fig. 1, sample K17-BS-1; Fig. 2). Stratigraphically higher Bullhead samples (RC18-SMSE-208, RC15-SW-95), including an ash with largely reworked sanidine, provide an MDA of 4.30 ± 0.09 Ma (Fig. 2) indicating that about one-third (by height) of the Bullhead Alluvium may have been deposited by this time. All the age data are consistent with the conclusion of Howard et al. (2015) that the onset of Bullhead aggradation occurred at ca. 4.5 Ma.

Blythe Basin

Three samples from various parts of the Bouse Formation (Table S4) in the Blythe Basin yielded three DS grains younger than ca. 5.3 Ma (Fig. 2). Of the 534 total DS grains, two grains from different samples define the MDA of 4.7 ± 0.5 Ma (Fig. 2).

Fish Creek–Vallecito Basin

We dated DS from the top of the Wind Caves member in the Fish Creek–Vallecito Basin. The analyzed material came from a paleomagnetic plug (sample 04PW30) collected by Dorsey et al. (2007). The sampled normal-polarity interval has a precise and robust MDA of 4.56 ± 0.04 Ma based on five tightly grouped DS grains (Fig. 2). The sample is stratigraphically above the first-arriving Colorado River sand from the base of the Wind Caves member, which is within a reversed-polarity interval (Fig. 3).

Part of the Earthquake Valley fault zone (California) separates the dated sample from first-arriving Colorado River sand. It is likely that those intervals are in the correct relative stratigraphic order, however, because the Wind Caves member is the only deep-marine turbidite succession derived from the Colorado River, and it occurs within a succession of units that do not repeat in this area. The change from local to Colorado River derivation occurs only once between the two samples, as documented in 21 measured sections of the Wind Caves member (Winker, 1987; Cloos, 2014; Dorsey et al., 2018), and there is only one change in polarity across this densely sampled part of the magnetostratigraphic section (Fig. 3; Dorsey et al. 2011). We correlate the reversed-polarity interval with the 4.80 to 4.63 Ma C3n.2r subchron (Fig. 3), during which the first-recorded Colorado River sands appear in the section. Detrital zircon dating (Cloos, 2014) also yielded four grains <5.3 Ma in the Wind Caves member, including a nearly concordant 4.6 ± 0.1 Ma grain from a similar (but slightly lower) stratigraphic position than

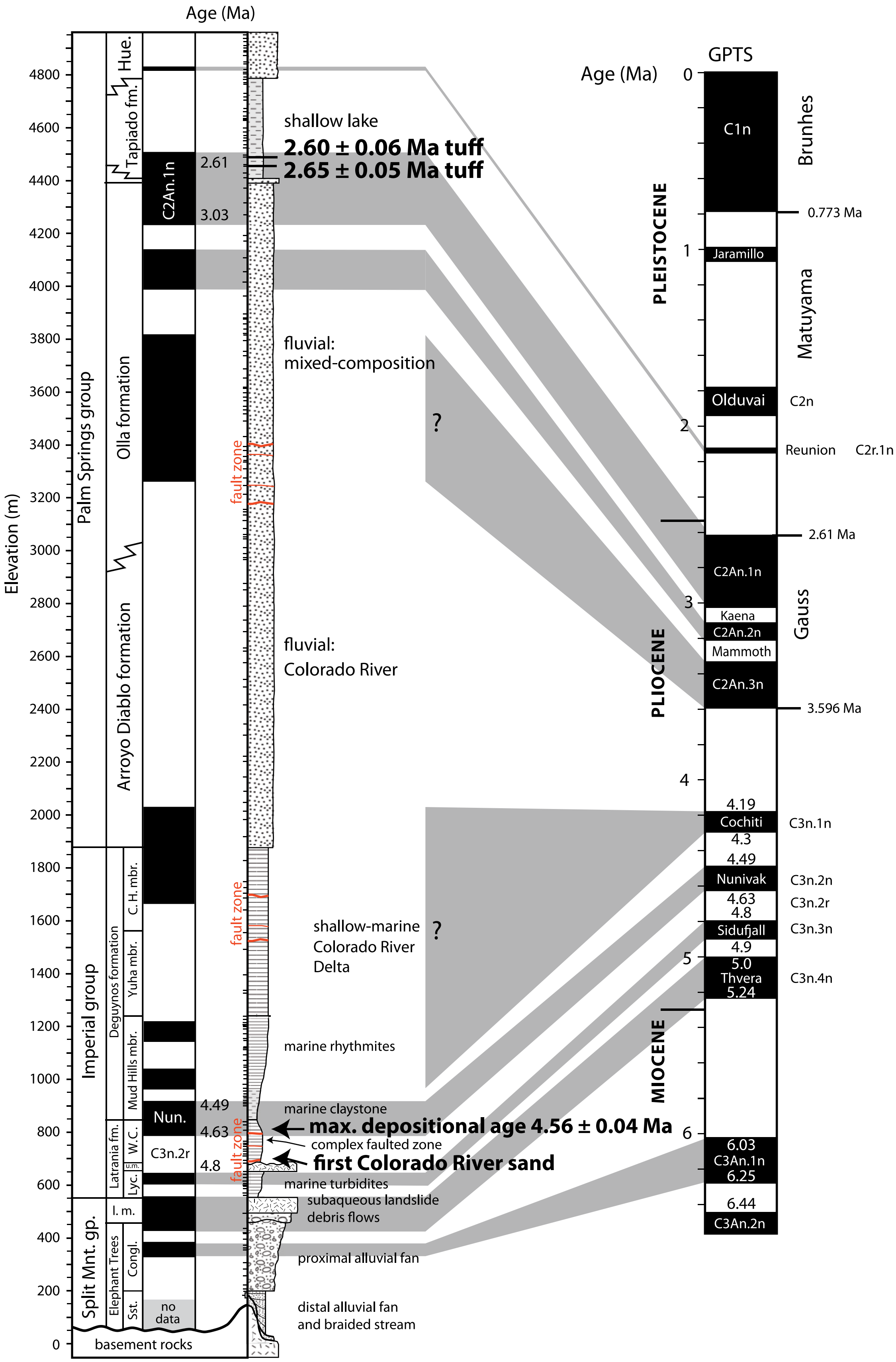

Figure 3. Composite section from the Fish Creek–Vallecito Basin (after Dorsey et al., 2011). Correlation to the global polarity time scale (GPTS) (Ogg, 2012; Channell et al., 2020) is shown where certain based on the new detrital sanidine ages from the upper part of the Wind Caves member and previous U-Pb results in the Tapiado formation, and queried where more work is needed. Also shown are positions of main fault zones (red lines) newly identified by Jänecke et al. (2016). sst.—sandstone; congl.—conglomerate; l.m.—lower mega breccia; Lyc.—Lycium member; u.m.—upper mega breccia; W.C.—Wind Caves member; C.H.—Camels Head member; Hue.—Hueso formation; Nun.—Nunivak subchron.

sample 04PW30. Altogether, ages from nine detrital grains indicate that the Colorado River arrived in the Fish Creek–Vallecito Basin during the early part of the Pliocene, ~0.5–0.7 m.y. after 5.3 Ma, the time of integration suggested by Dorsey et al. (2011).

The discovery of at least three major strands of the Earthquake Valley fault zone in the >5 km stratigraphic section (Jänecke et al., 2016; Fig. 3), which separate the only radiometric calibration points from the first Colorado River sands (Fig. 3), provides an explanation for the

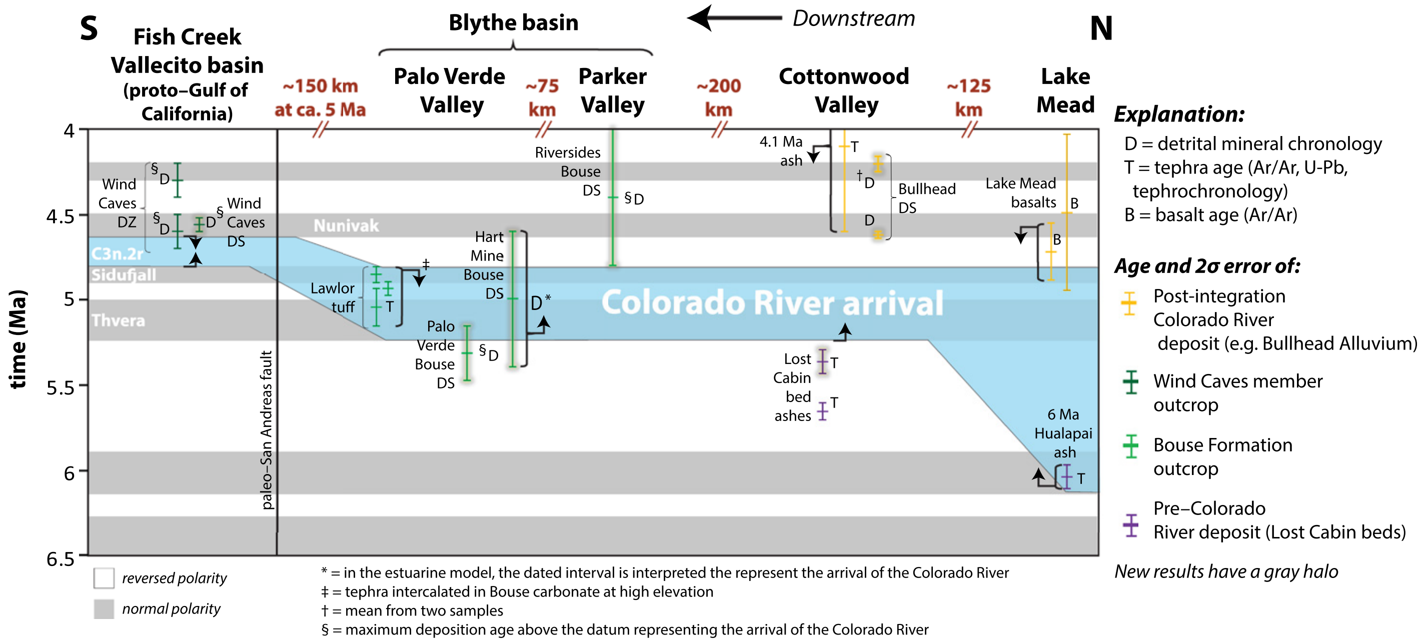

Figure 4. Summary figure showing, in blue, permissible timing of Colorado River arrival to locations below Grand Canyon. Arrows point toward the time of Colorado River arrival. Polarity intervals (names labeled in white) are from Ogg (2012) and Channell et al. (2020). DS—detrital sanidine age; DZ—detrital zircon age.

discrepant ages on the first Colorado River sand deep in the section (Dorsey et al., 2007, 2011). The initially missed right-oblique fault strands are subparallel to bedding and contain sheared mudstone, and one trace resembles an olistostrome. Further work will likely show that the Earthquake Valley fault zone, along with many strands of the Split Mountain fault zone, duplicated polarity intervals.

DISCUSSION AND CONCLUSIONS

Improved constraints on the timing of Colorado River arrival to the lower Colorado River corridor have implications for the depositional environment of the Bouse Formation, the amount of regional uplift, and the processes of river integration. The constraints, along with their errors, shown in Figure 4 indicate that (1) deposition of the northern Bouse Formation began after 5.24 Ma, and (2) Colorado River sediment preserved in the Wind Caves member first arrived to the GOC between 4.80 and 4.63 Ma. These constraints are linked to the GPTS, which has been precisely determined by correlation to the Earth's precession cycle for the Plio-Pleistocene (Lourens et al., 1996). Neither constraint is consistent with the previously proposed 5.3 Ma age of initial integration (Dorsey et al., 2011). The relatively poor-precision DS results of Blythe Basin Bouse deposits are permissive of this conclusion, but not critical to it.

The new age model for Wind Caves member in the Fish Creek–Vallecito Basin also suggests that the oldest marine deposits there may be ca. 5 Ma and that coarse basal alluvial fans below them started forming after 6.4 Ma (Fig. 3). The revised ages are consistent with the sudden onset of significant plate-boundary motion and basin subsidence in the Salton Trough and northern GOC at 6–6.5 Ma (Oskin and Stock, 2003).

The new data constraining first arrival of sand from the lower Colorado River *are* consistent with previous interpretations that the 5.0–4.9 Ma Lawlor Tuff, which is interbedded in Bouse Formation basal carbonate at some of the highest outcrops in the Blythe Basin, predates the arrival of Colorado River sediment to the GOC (e.g., Spencer et al., 2013) (Fig. 4). Dorsey et al. (2018) argued that the Colorado River arrived in the GOC prior to the eruption of the Lawlor Tuff and that Bouse deposits associated with the tuff record a second marine inundation of the Blythe Basin. In such a model, ~300 m of post–5.0 Ma regional uplift would have been required to raise the Bouse Formation interbedded with Lawlor Tuff to its current elevation of ~300 m, because modern sea level is within <20–50 m of its Pliocene levels (Miller et al., 2011). The new geochronology does not support this multi-stage model. Deposition of the Lawlor Tuff in the Blythe Basin can now be shown to have pre-dated the first arrival of Colorado River detritus to the GOC at the 95% confidence level (Fig. 4). The interpretation favored here is that the upper facies of the Bouse Formation is a progradational offlap sequence associated with lowering lake levels rather than a second marine incursion (Gootee et al., 2016) and that there was a single fill, spill, and incision sequence in the Blythe Basin (possibly after a pre-integration marine incursion), consistent with downward integration (House et al., 2008; Spencer et al., 2013; Pearthree and House, 2014). Prior to this integration event, any river system responsible for the partial excavation of Grand Canyon (Wernicke, 2011; Karlstrom et al., 2014) must have terminated elsewhere.

The new geochronologic constraints indicate that Bullhead Alluvium started to accumulate during or soon after cessation of Bouse Formation deposition. Colorado River sediment arrived at the sea between 4.80 and 4.63 Ma, and Bullhead Alluvium was being deposited in Cottonwood Valley by as early as 4.6 Ma. In the Lake Mead area, Bullhead Alluvium was already being deposited when the 4.5 Ma Sandy Point basalt was erupted (Faulds et al., 2016). Base-level differences between previously closed basins connected during integration likely led to rapid incision focused at paleodivides as an equilibrium profile was established (Pearthree and House, 2014; Crow et al., 2019). The liberated sediment from these and upstream profile adjustments, including in Grand Canyon and upstream (Howard et al., 2015), likely produced more sediment than could be transported through the system, leading to widespread Bullhead aggradation throughout the corridor. The new results indicate that the lower Colorado River was born via downward-directed processes at least half a million years later than indicated by Dorsey et al. (2011).

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