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Research Article

Sedimentary record of annual-decadal timescale reservoir dynamics: Anthropogenic stratigraphy of Lake Powell, Utah, U.S.A.

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ABSTRACT The tributaries of Lake Powell were impounded following construction of Glen Canyon Dam, resulting in deposition of reservoir sediment over a ∼650 km^2 area since 1963. These units have been exposed through erosion as water storage in Lake Powell has decreased since 2000. This anthropogenic sedimentary record reflects the complex interplay among wet and dry periods of Colorado River runoff and the reservoir operating rules of Lake Powell. The relevant sedimentary exposures are mapped at reconnaissance level over 300 river-km above Glen Canyon Dam in canyons of the Colorado, San Juan, Escalante, and Dirty Devil Rivers. A detailed reference section measured in Calf Canyon, a tributary to the Colorado River, preserves more than 12 m of lacustrine, mainstem Colorado River, and local tributary sediment in an up-river location and elevation that is determined to have been inundated only during the highest reservoir level periods. At Calf Canyon, exposed reservoir sediment is comprised of cyclic sand-mud interbeds that record periods of deposition when reservoir level was at or above full pool. Six depositional cycles are identified in Calf Canyon, and each of these is interpreted to represent rapid sand deposition during Colorado River flood events (likely related to spring snowmelt runoff) followed by deposition of lacustrine mud while reservoir levels were high. The lacustrine mud units display significant pedogenic modification, indicating exposure and colonization dominated by tamarisk plants, prior to deposition of the next sand unit. High-precision elevation surveys of the 6 main lacustrine marker beds in Calf Canyon are correlated to multiple lake level highstands between 1975 and 2000. Preliminary observations suggest that age-equivalent strata are widespread within the reservoir-affected zones of all major tributaries including the Colorado and San Juan River arms as well as the Escalante and Dirty Devil Rivers. We predict that future mapping in other Lake Powell side canyons will demonstrate strong local control on sediment provenance, dictated by side canyon lithology, as well as time-transgressive deposition (and erosion) moving up and down the main canyons.

KEYWORDS Glen Canyon Dam, Lake Powell, Upper Colorado River Basin, Anthropocene, aridification, megadrought, reservoir management, fluvial, lacustrine, deltaic, sediment

INTRODUCTION

Completion of Glen Canyon Dam in 1963 impounded nearly 300 km of the Colorado River and its tributaries, creating Lake Powell (Fig. 1). The dam was authorized by the Colorado River Storage Project Act of 1956, and the water storage and hydroelectricity provided by the dam played an important role in the economic development of the American West. Lake Powell, located immediately upstream from the Grand Canyon, is the second largest reservoir in the U.S., and Lake Mead reservoir, the largest in the U.S., is located ∼400 km downstream at the lower end of the Grand Canyon. Together, these two reservoirs create ∼80% of the total reservoir storage capacity of the watershed and help ensure a secure and reliable water supply for tens of millions of users (James et al., 2014). Allocation of the water supply provided by the Colorado River has been negotiated in an aggregation of interstate compacts, Supreme Court decisions, statutes, administrative agreements, and a bi-national treaty collectively called the Law of the River. The most recent revisions of the Law of the River were the Colorado River Interim Guidelines for Lower Basin Shortages and Coordinated Operations of Lake Powell and Lake Mead, negotiated in 2007, and the Drought Contingency Plan, negotiated in 2019 (Bureau of Reclamation, 2020).

These recent agreements were necessitated by declining reservoir storage resulting from the megadrought that began in 2000, referred to as the Millennium Drought of the western United States (Xiao et al., 2018), or alternatively the turn-of-the-twenty-first-century drought (Williams et al., 2022). Runoff into Lake Powell was 12.3 million acre

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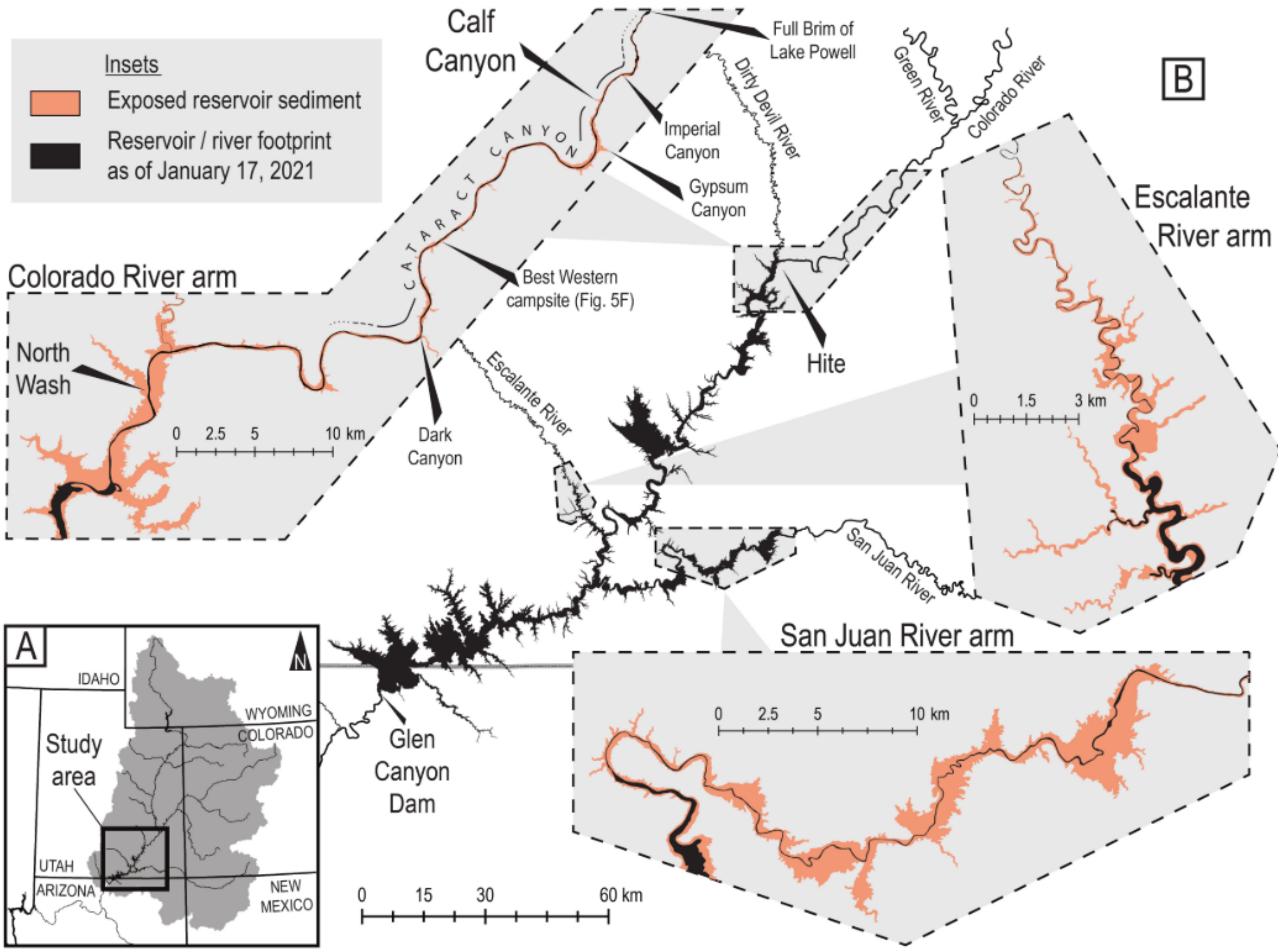

Figure 1: Location map of the study area and Lake Powell in the western United States. (A) Lake Powell straddles the Utah-Arizona border and represents the lowermost reach of the Upper Colorado River Basin (grey). (B) The footprint of Lake Powell is shown at its maximum extent, with insets (dashed) focused on the Colorado, San Juan, and Escalante River delta regions. Sediment deposited during highstands, particularly where rivers meet the reservoir, is exposed while lake level remains low. The lake footprint as of January 17, 2021, is illustrated in each inset and is drawn from Sentinel-2 satellite photos courtesy of the U.S. Geological Survey.

feet/yr between 2000 and 2021, which was 14% less than the average annual natural flow between 1930 and 1999 and was one of the most severe droughts of the past 1000 years, as estimated by tree-ring hydrology (Meko et al., 2007; Salehabadi et al., 2020). Williams et al. (2020) argued that this record represents the onset of a megadrought in the watershed, and that present soil moisture conditions are the second worst in the last 1200 years (see also Woodhouse et al., 2010; Udall & Overpeck, 2017); updates to this analysis indicate that the drought has intensified between 2020–2021 (Williams et al., 2022). Recent projections of Lake Powell water storage (Bureau of Reclamation, 2021), from spring 2022 to spring 2024, have included the possibility that the reservoir will nearly drop to an elevation below which hydroelectricity cannot be produced at Glen Canyon Dam (Bureau of Reclamation, 2007). If recent conditions represent the "new normal" of an aridifying climate, reservoir sediments accumulated during the filling of Lake Powell may leave a widespread, persistent, and well exposed record of sedimentary processes that inform our understanding of how lakes fill and evacuate sediment.

The post-2000 reservoir lowstand has extensively exposed reservoir sediment within the Colorado, San Juan, Dirty Devil, and Escalante arms of Lake Powell (Fig. 1). In each arm, the delta that had formed during reservoir highstand was reworked when the reservoir level declined, and the reworked sediments contributed to delta front progradation, as documented by numerous bathymetric studies (Pratson et al., 2008; Majeski, 2009; Andrews et al., 2018; Poppenga et al., 2020; Jones & Root, 2021). The management of reservoir sediment in Lake Powell has long been an issue of societal and scientific discussion (McPhee, 1971; Potter & Drake, 1989; Reisner, 1993), initially addressed only by documenting sediment influx and sediment accumulation (Gessel, 1963; Condit et al., 1978; Ferrari, 1988). Questions regarding the future fate of reservoir sediment in Lake Powell are becoming tractable due to both spatially extensive modern datasets and low lake level (e.g., Andrews et al., 2018; Hynek et al., 2021). There is concern about remobilization of large volumes of fine sediment and the possible impacts of contamination to water quality caused by metal and nutrient cycling of mining waste that is part of some of the Lake Powell delta sediments (Stanford & Ward, 1991; Vernieu, 1997; Wildman & Hering, 2011; Frederick et al., 2019; Kasprak & Schmidt, 2019).

The instrumental record of the Colorado River is robust: gaging began in the late 19th century and reservoir elevation has been recorded daily since late 1963 (United States Geological Survey, 2022; Bureau of Reclamation, 2022). Based on this high-resolution instrumental record, the history of reservoir water storage comprises three main phases (Fig. 2): the prolonged period of filling from 1963–1980, the period of fluctuating highstand in the 1980s and 1990s, and a prolonged lowstand since 2000. The mid-1980s highstand was caused by unusually large runoff between 1983 and 1986. The Millennium Drought has included a few singular wetter-than-average years, but the overall decline in Lake Powell water storage has been progressive. We hypothesize that the sedimentary record of reservoir sedimentation can be tied to the decadal-scale history of water storage (Fig. 2) and broadly ascribed to transgressive, highstand, and regressive-to-lowstand phases, respectively. The relationship between this lake level record and sedimentation is the primary focus of this study.

Here, we describe and interpret the stratigraphic record of reservoir sediment in Calf Canyon, a side canyon tributary to the Colorado River arm of Lake Powell (Fig. 3). Calf Canyon is within 6 river km of the maximum upstream end of Lake Powell, and we anticipated that reservoir sedimentation would only preserve the evidence of historical high stands of the 1980s. This study may serve as a reference for understanding reservoir depositional processes that can be extended and modified to other parts of Lake Powell and to other reservoirs (cf. Wu et al., 2020). This study links sedimentary deposits to annual- and decade-scale reservoir and river dynamics and demonstrates the potential for future studies of anthropogenic strata exposed in reservoirs throughout the western U.S., and potentially globally where dwindling water resources create similar scenarios.

METHODS

Aerial mapping of exposed sediment footprint

Geospatial analysis of historical and modern topography provides a foundation for mapping the aerial extent of sediment deposited in Lake Powell (Fig. 1). A pre-Glen Canyon Dam digital elevation model (Root et al., 2019) and recent topobathymetry (Poppenga et al., 2020) were differenced to illustrate where changes between ground-surface and reservoir-bottom elevations had occurred. The extents of Lake Powell are qualitatively verified with Landsat satellite imagery (Fig. 3A). Historical photography with modern photo-matching also served to document site-specific changes in the reservoir as water level changed (Returning Rapids Project, 2022, Fig. 3D,E).

Reconstruction of the history of reservoir elevation in the study area

The Bureau of Reclamation has reported a daily water-surface elevation of Lake Powell since December 1963 (Bureau of Reclamation, 2022). The elevation is recorded from a stilling well inside Glen Canyon Dam and reported relative to the National Geodetic Vertical Datum of 1929; these elevations, and all other elevations reported here, are converted to the North American Vertical Datum of 1988 (NAVD 88). The USGS has reported water-surface elevation at Glen Canyon Dam (USGS site 09379900, United States Geological Survey, 2022), using 15-minute averages from radar measurements off the water surface near the dam, since April 2019. Approximately 200 km upriver from the dam, the USGS has monitored water-surface elevation at the Utah State Route 95 bridge near Hite, UT (USGS site 09328990) since December 2016. Data from this location represent Lake Powell when the reservoir is above ∼1,100 m or the Colorado River when the reservoir is below ∼1,100 m.

When the reservoir elevation of Lake Powell is greater than ∼1,100 m (and extends past Hite), the water-surface elevation at Hite is not equal to that at the dam, particularly when flow in the Colorado River is high (>850 m^3/s; Fig. 2B). We resolve this discrepancy to better constrain reservoir level in the upper Colorado River arm during periods of high flow. We use the sum of the mean daily discharge at the Colorado River near Cisco, UT (USGS site 09180500), Green River at Green River, UT (USGS site 09315000), and San Rafael River near Green River, UT (USGS site 09328500) to represent Colorado River flow at Calf Canyon (U.S. Geological Survey, 2022). The Dirty Devil River, which meets the Colorado River near Hite, is omitted as it is ∼50 km downriver from the study site. The Colorado and Green River gages are located 155 km and 195 km, respectively, upriver from the Hite bridge, and there is comparatively little inflow downstream from either (Walker et al., 2020; Wang & Schmidt, 2020).

A polynomial regression, based on the relationship between the water-surface elevations at Hite and at Glen Canyon Dam between 2016 and 2021, is used to estimate the water-surface elevation at Hite during the highstand between 1975 and 2000 (Fig. 2B). The difference in water-surface elevation can be on the order of 1 m between these two sites during periods of high flow. This approach underestimates the water surface elevation of the reservoir in the Colorado River arm, because we expect the reservoir surface to have additional slope between Hite and the study site during periods of significant discharge. As such, the error in correlating historical reservoir elevations to the elevation of specific sediment beds in the Calf Canyon section is on the order of 1 m and likely systematically biased

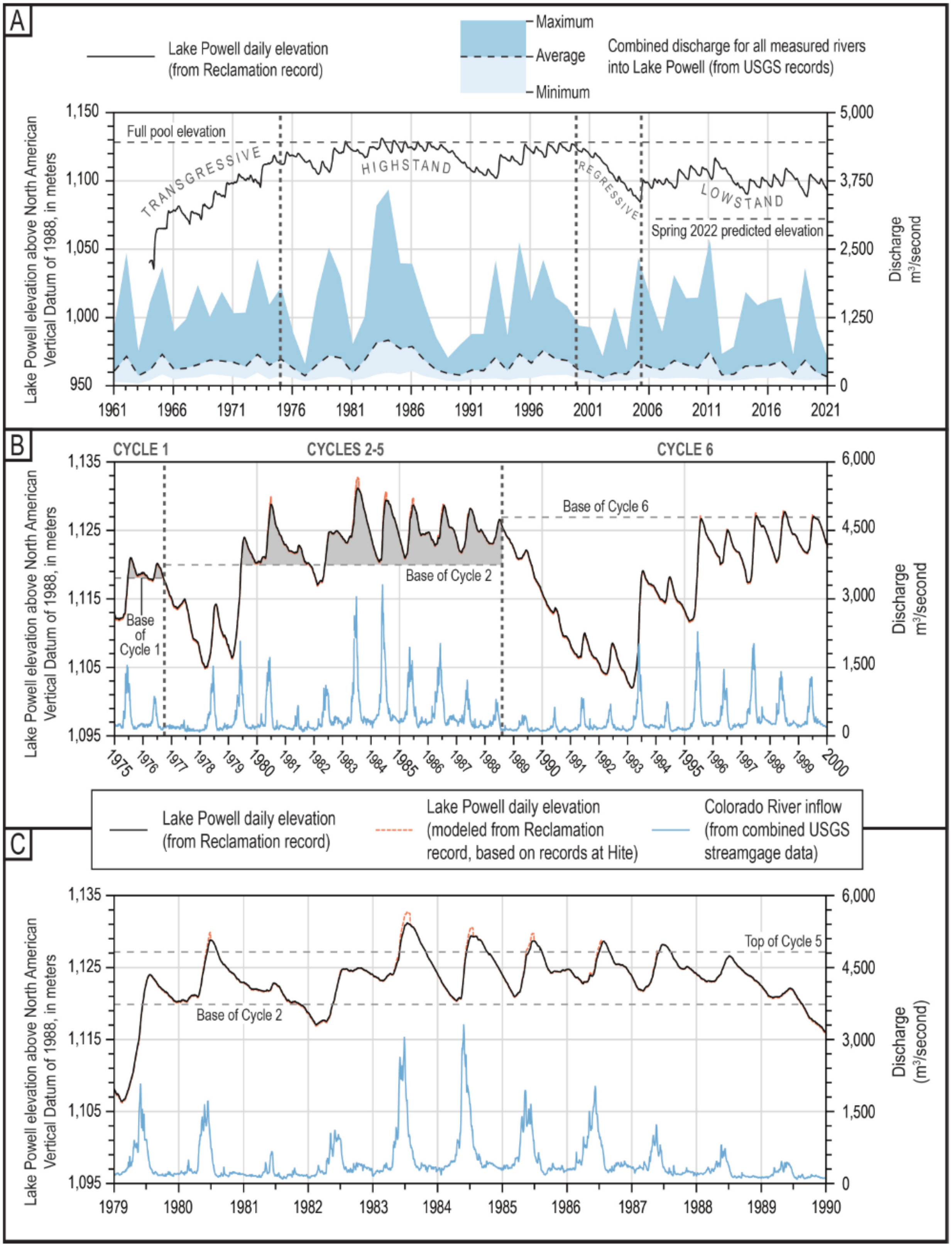
A
Lake Powell daily elevation (from Reclamation record)
Maximum
Average
Minimum
Combined discharge for all measured rivers into Lake Powell (from USGS records)
Full pool elevation
TRANSGRESSIVE
HIGHSTAND
REGRESSIVE
LOWSTAND
Spring 2022 predicted elevation
Lake Powell elevation above North American Vertical Datum of 1988, in meters
Discharge m3/second
B
CYCLE 1
CYCLES 2-5
CYCLE 6
Base of Cycle 6
Base of Cycle 2
Base of Cycle 1
Lake Powell daily elevation (from Reclamation record)
Lake Powell daily elevation (modeled from Reclamation record, based on records at Hite)
Colorado River inflow (from combined USGS streamgage data)
C
Top of Cycle 5
Base of Cycle 2
Discharge (m3/second)

Figure 2 ***(previous page)*:** (A) Reservoir level history (left axis), as reported by the Bureau of Reclamation (2022) and converted to NAVD 1988, and combined discharge history of all monitored rivers that source Lake Powell (right axis). The discharge record shows the calendar-year average (black dashed line) as well as the maximum and minimum single-day discharges within each calendar year. These annual values are derived from daily records at gages nearest to Lake Powell for the Colorado (near Cisco, UT - USGS site 09180500), Green (at Green River, UT - 09315000), San Juan (near Bluff, UT - 09379500), San Rafael (near Green River, UT - 09328500), Dirty Devil (above Poison Springs Wash near Hanksville, UT - 09333500), and Escalante (near Escalante, UT - 09337500) Rivers (United States Geological Survey, 2022). Reservoir elevation marks (gray dashed lines) show the full-pool elevation and the most probable elevation for April 2022 (Bureau of Reclamation, 2021). The interpreted phases of reservoir level linked to stratigraphy are labeled (transgressive, highstand, regressive, and lowstand). (B) This study focuses on fluctuation in reservoir level between 1975 and 2000 when Lake Powell was high enough to inundate Calf Canyon as sediment was progressively deposited (highlighted in gray here, see Fig. 1 for location). Shown are daily records of Bureau of Reclamation-reported reservoir level, modeled reservoir level, and discharge of the combined flow of the Colorado, Green, and San Rafael Rivers between 1975 and 2000. The sum of these gages approximates the expected flow into Lake Powell from the Colorado River only. Depositional cycles (c.f. Fig. 4) sequentially raise the minimum required elevation for inundation. The modeled level is based on reservoir level records higher than approximately 1,100 m above NAVD 88 from 2016 to present at Hite, UT (USGS site 09328990), and informed by the discharge history. During high flows (>850 m^3/second), the reservoir level in the Colorado River above Hite may be on the order of 1 meter higher than at the dam, and was estimated as: $y = 0.0018854794352432x^2 - 12.7757284019419x + 25160.8556439604$, where y is the water surface elevation at the Colorado River delta and x is the elevation reported by Bureau of Reclamation. On days when the estimated reservoir inflow was less than 850 m^3/s, reservoir elevation in the Colorado River arm (y) was estimated as: $y = 0.00023415357539847x^2 - 0.707904674059232x + 3,113.70503085849$. (C) Period of 1979 to 1990 from Panel B, highlighting depositional cycles 2–5.

low during periods of high discharge.

Site description at Calf Canyon

Reservoir sediment in Calf Canyon was targeted for study because this side canyon has excellent exposures of interbedded reservoir mud and sand layers encased within pre- and post-reservoir alluvial/colluvial deposits. This site (38.03265, -110.07116 at the base of the section) is 6 km downstream from the maximum extent of Lake Powell (Figs. 1, 3), making this location ideal for investigating fluctuations in reservoir level during the highstand interval. Some river guides label this location Waterhole Canyon (e.g., Belknap & Evans, 2019), and this is an acknowledged variant name for Calf Canyon; however, the officially-named Waterhole Canyon is located about 7 km west of Calf Canyon and is a tributary to Clearwater Canyon (United States Board of Geographic Names, 2022). In 2015, the elevation of the Colorado River at the mouth of Calf Canyon was approximately 1111 m, whereas the top of the reservoir sediment was approximately 1129 m, based on a 0.5-m DEM (Utah Geospatial Resource Center, http://gis.utah.gov). These preliminary elevations constrain a narrow time span when Lake Powell was sufficiently high to deposit sediment at Calf Canyon (Fig. 2).

The stratigraphic section was measured using a Jacob staff with a height-adjustable Abney level, cross-checked with elevation data for the main marker beds, and was described using standard sedimentologic descriptions such as grain size, lithology, bedding contacts, sedimentary structures, and biogenic features. Samples of weakly indurated fine sediment were collected from the 13 primary beds in the reservoir section, and the samples were later examined for color and grain characteristics including size, shape, sorting, and mineralogy using a reflected light binocular microscope at 1–3x magnification.

The tops of each major unit were marked with a reference flag and surveyed with ground-based topographic mapping using Leica GS14 GPS receivers, resulting in a Level IV campaign (Rydlund & Densmore, 2012). A base station collected data in an open area on top of the reservoir sediment on the north side of Calf Canyon, while a remote unit (rover) communicating with the base station was used to survey the elevation of reference flags, other stratigraphic levels, and key landscape features. The average vertical uncertainty for positions measured with the rover was ~2.5 cm. The base station data were post processed using the National Geodetic Survey's Online Positioning User Service (OPUS, https://www.ngs.noaa.gov/OPUS/), yielding a total vertical uncertainty of 7.7 cm for the base station. All rover positions were corrected to this elevation, and this vertical uncertainty accurately represents the dataset; horizontal position accuracy is better, though unsubstantiated.

In October 2020, we measured the water surface elevation of the Colorado River immediately upstream from Waterhole Canyon Rapid (Belknap & Evans, 2019) to be 1110.9 m, and 1110.2 m at the mouth of Calf Canyon (15 m downstream, in the middle of the rapid). Reservoir sediment upriver from Calf Canyon and on the right bank of the Colorado River is exposed along a terrace that was measured to range in elevation between 1128.3 to 1129.7 m; this surface was extensively colonized by tamarisk (Tamarix spp.). The tamarisk on this surface are presently dead or dying and are largely restricted to the highest elevation surfaces of reservoir sediment, although some individual plants were rooted in colluvial material to an elevation of ~1132 m. At the head of Calf Canyon, above the level of any reservoir or side-canyon derived sediment, a few large driftwood logs lay on top of coarse colluvium that partially mantled a steep bedrock slope. The GPS rover could not communicate with the base station at this location, so an elevation of ~1132 m, was estimated by sighting up canyon with an Abney level from the nearest reliable GPS observation. Lacustrine deposition at elevations of 1132 m can only be achieved by modeled lake level in 1983 (cf. Fig. 2B).

RESULTS

Observations of Calf Canyon Section

The reference section measured at Calf Canyon comprises ~12 m of interbedded sand and mud units exposed between 1118–1130 m (Figs. 4, 5A). The units range from poorly- to well-indurated, and here we elect to use sediment rather than lithologic terms (i.e., mud vs mudstone), but we note that the mud deposits are significantly more indurated than the sand deposits. This section overlies, with an uneven surface, ~2 m of gravel exposed in the mouth of the canyon, and the sand-mud section is overlain by at least 7 m of gravel near the head of the canyon on the north side (Fig. 3B, section top, 38.03392, -110.07307). The drafted section focuses on the main marker beds for which elevations were measured within Calf Canyon. We note that finer-scale stratigraphic variations, including additional mud units <10 cm thick, minor gravel lags, as well as some minor lateral facies variations, are not depicted.

Both the upper and lower gravel sections are poorly sorted, with clast size ranging from granules to large boulders with average diameters of ~10–30 cm (Fig. 5C). Clasts are primarily angular to subangular sedimentary rocks that appear to match the lithology of the Upper Carboniferous Honaker Trail Formation (Hermosa Group; Fig. 3A) that is exposed in the upstream tributary watershed. The matrix of these gravel deposits is mainly fine sand to silt. (Fig. 5C). Crude dm- to m-scale bedding demonstrates both matrix-supported and clast-supported intervals, the latter exhibiting imbrication indicating down-canyon (towards the mainstem Colorado River) flow as well as inverse-grading at the tops of several beds, particularly in the basal units.

The interval of primary interest at Calf Canyon includes seven main sand units, ranging from 0.25–2 m thick (Figs. 4, 5A). The lowermost of these beds shows a lateral facies transition from sand to mud as the bed is traced more than 10 m laterally WNW, up Calf Canyon. These partially indurated beds are comprised of mainly fine-grained sand with typically sharp, flat basal contacts. The uppermost 5–10 cm of the sand beds commonly fine upwards to very fine sand and silt, forming a gradational upper contact with the interbedded mud layers (Fig. 5B).

The sand beds exhibit some massive to planar bedding, but typically transition upward to climbing ripple cross laminations and in some cases, are capped by stacked oscillatory ripples, immediately below the overlying mud bed (Fig. 5B). Larger-scale cross bedding is rare and few possible trough cross beds were observed; there are occasional outsized grains (granules to pebbles) forming lags at the bases of some of these units. Climbing ripple sets have a range of expressions from steep, well-defined climbing ladders, to extremely low-angle ripple chains stacked up to 50-cm thick (cf. Allen, 1973). Individual ripple crests are typically <2 cm tall and show evidence of both supercritical and subcritical climb, with variable preservation of stoss-side laminae (Hunter, 1977). Flow during deposition is commonly oriented up Calf Canyon (average 325°, WNW). A detailed examination of one of these sand units (the lower part of cycle 5 starting at 1123.75 m, Fig. 4) revealed a lateral transition moving up Calf Canyon over a distance of ~80 m, from supercritical climbing ripples (25–27 degrees), to subcritical (<20 degrees) climbing ripples, to vertically-stacked symmetric/oscillatory ripples, to planar lamination. Similar successions are seen stacked vertically throughout the section (Fig. 5B).

Sands in the lowermost part of the section are tan to light brown-colored, with the exception of a few minor pink sand beds such as at ~1122 m. At ~1127 m, a more persistent change to pink sands up-section is observed (Figs. 4, 5E,F). Overall, microscopy of grain mounts from samples of the sand beds shows abundant quartz and feldspar grains with variable lithic fragments, organic matter, and mainly subrounded to rounded grains. The pink-colored sands are slightly coarser grained (up to medium-grained sand) and have occasional coarser-grained granule to small gravel lags at the base. They are typically more massive and lack climbing ripple cross lamination that are more common in the other sand units. Compositionally, the pink sands contain iron oxide-stained quartz, whereas the brown sands are slightly finer-grained, better sorted, and contain detrital mica.

Six distinct mud units are interbedded with the sand units between 1118.52–1128.15 m (Fig. 4). These beds range from 0.2–1.1 m thick and are typically light pink-colored, tabular, and relatively well indurated. Whereas the tops of several sand units fine upwards into silty mud, the main mud beds contain both clay and silt, and have gradational to distinct bases and sharp upper contacts with overlying sand units. Oxidation rims and, in some cases, plant material are common in the upper few cm of these beds as rootlets (<1 cm in diameter). Two of these mud units form more extensive ledges in the outcrop, and the uppermost bed (up to 1127 m, Fig. 4) contains large casts from tamarisk roots and extensive vegetation-induced sedimentary structures creating pedogenic textures (Fig. 5D,E; cf. Dean et al., 2011). The uppermost mud bed is overlain by poorly indurated coarse sand and large clasts in talus at the head of the canyon.

Interpretation of Calf Canyon Section

Gravel units in Calf Canyon are interpreted as alluvial/colluvial deposits (cf. Miller & Juilleret, 2020). The basal units are interpreted as mainly debris flow deposits given the prevalence of large clasts in poorly sorted to inversely graded, matrix-rich deposits. The upper units overlying the main sand-mud succession are typically clast-supported, indicating traction-dominated flash flood deposition and post-depositional stream reworking (Blair, 1999).

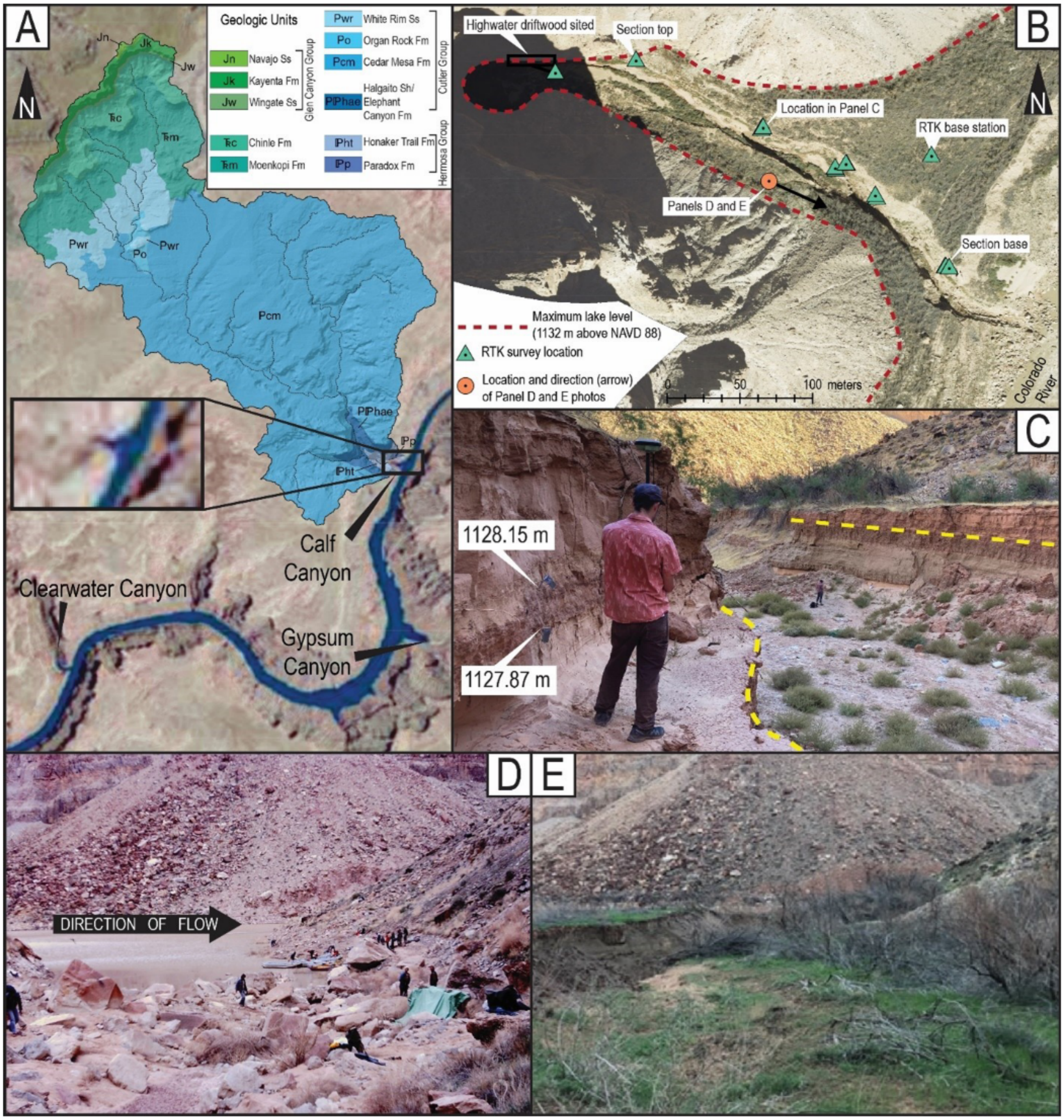

Figure 3: (A) Calf Canyon and its surrounding terrain. The underlying satellite photo, a Landsat-5 image courtesy of the U.S. Geological Survey, was taken on June 27, 1984 during a period of high reservoir level and high river discharge. Though its resolution is limited, the blue wedge of water (inset) affirms Calf Canyon was flooded during this period. The Calf Canyon watershed (30.6 km^2) and flow network (United States Geological Survey, 2018) are shown with bedrock geology (from National Park Service (NPS) Geologic Resources Inventory (GRI) program), highlighting the potential sources and transport paths for locally derived sediment. (B) A higher resolution orthophoto from October 2015, acquired by Canyonlands National Park in partnership with the Utah Division of Forestry, Fire and State Lands (B. Ehler, personal communication, March 12, 2021), shows the survey markers and lake deposits in Calf Canyon. (C) Outcrop photo of the upper Calf Canyon section. An RTK rover elevation is taken atop a prominent lake bed which is traced across the canyon (dashed yellow line). Other survey elevations, in meters relative to NAVD 88, are noted including the uppermost lake sediment at 1127.87 m. In the lower two panels are photos, taken from the same location, looking southeast down Calf Canyon and across the Colorado River from April 1980 (D) and March 2019 (E; Returning Rapids Project, 2022).

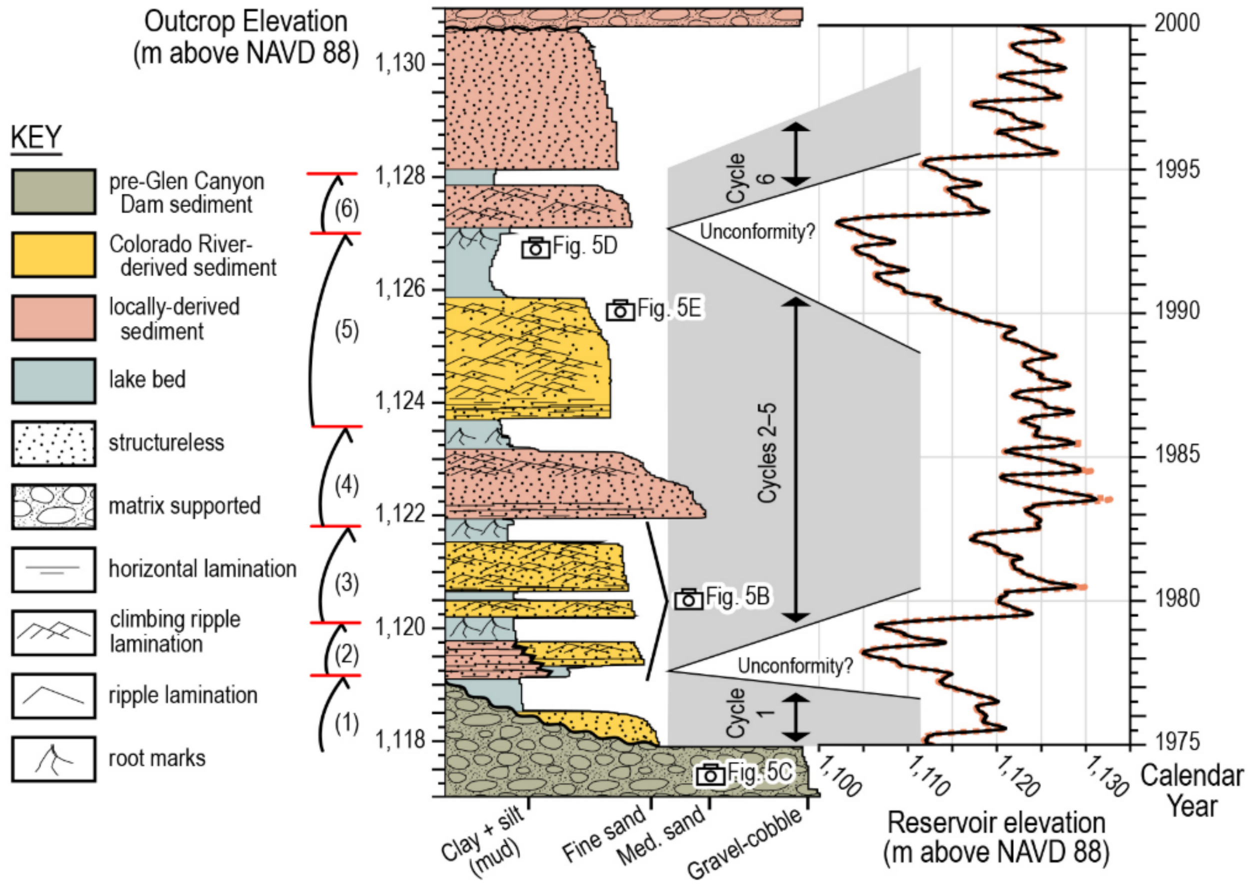

Figure 4: Stratigraphic section of reservoir sediment and daily reservoir elevation. The reservoir record includes the published (black line; Bureau of Reclamation, 2022) and modeled (orange dotted line) records. Interpreted depositional cycles (sand-mud bed couplets) are labeled on the left; curved arrows represent 6 cycles of upward-deepening deposition, separated by exposure surfaces (red lines). Potential correlations of these cycles to the lake level record are depicted in gray, with cycles 2–5 undifferentiated within the 1980–1988 fluctuating highstand period. Periods of time when reservoir level was below the surveyed depositional height of units in Calf Canyon are interpreted as non-depositional unconformities.

In the case of the lower gravel unit, reservoir strata onlap a steeply dipping pre-reservoir land surface which increases in elevation both up Calf Canyon (WNW) and southward from the main exposures. The lower unit was present prior to deposition of the main sand-mud interval, further evidenced by up-canyon onlap of the lowermost sand bed onto the undulatory surface of the basal gravels. Exposures of the upper gravels are confined to the head of Calf Canyon, but their stratigraphic superposition with respect to reservoir sediment and its presence only above 1130 m indicates deposition occurred in the interval between regression of Lake Powell and the post-abandonment incision and exposure of the reservoir section (i.e., during the last 20 years).

The sand-mud interval in Calf Canyon is interpreted as the main reservoir-fill succession, meaning these units were deposited during periods when backwater effects and/or inundation of Lake Powell reached the elevation of sedimentation in Calf Canyon (Fig. 2; Maselli et al., 2018). Climbing ripple cross laminations in the sand beds indicate rapid sedimentation (Allen, 1970; Ashley et al., 1982) and in most cases, local currents moving up the side canyon, away from the Colorado River, during deposition. These beds are interpreted to reflect deposition during seasonal during seasonal high flow of the Colorado River (i.e., annual snowmelt runoff) with both surge-stage and waning-flow sedimentation possible (cf. Jobe et al., 2012; Plink-Björklund, 2015). In the Cycle 5 sand bed, the observed transition from supercritical to subcritical climbing ripples, symmetric ripples and planar lamination, is interpreted to represent waning flow conditions over a lateral distance of ∼80 m during a single depositional event (sand bed of Cycle 5) where Colorado River sands were transported up into Calf Canyon.

The upper contacts of the sand beds typically fine upwards and are transitional into the overlying mud unit, which is interpreted as lacustrine deposits. Based on our preliminary provenance assessment, sediment in the lower section is likely derived from the Colorado River and was moved up into Calf Canyon during high flow phases. In contrast, the upper pink sands are likely derived from bedrock units exposed at the head of Calf Canyon and in its drainage area above the canyon rim (Fig. 3A). These locally derived sediment contributions are linked to localized precipitation and not snowmelt runoff of the mainstem Colorado; the pink admixture to the thick sand in the middle of the section ($\sim$1122 m) likely represents a large local precipitation event and resultant flash flood.

Mud layers in Calf Canyon are interpreted as lake beds deposited in the reservoir. Specifically, the six main lake beds (Fig. 4) are inferred to represent reservoir highstands when Lake Powell reached the elevation of Calf Canyon for long enough that fine-grained lacustrine sediment could accumulate. Common gradational contacts with underlying sand units suggest that some of these highstands (occurring over several-year periods) could have been preceded by a Colorado River flow event leading to a period of rising reservoir levels and local inundation permitting sustained sedimentation in Calf Canyon. This depositional scenario is consistent with annual cycles of reservoir operations where the lowest reservoir levels occur in early spring, which brings fluvial sediment, attendant reservoir level rise, and subsequent high reservoir levels that are relatively stable for much of the summer and fall (Fig. 2C). In contrast, the upper contacts tend to be sharp and commonly marked by tamarisk rootlets and, in some cases, more extensive pedogenic modification. These surfaces are likely minor unconformities indicating reservoir level drop, exposure of the reservoir sediments, and initial colonization by tamarisk, which is eventually removed or buried in a subsequent flood and associated sedimentation event (Dean et al., 2011, 2020).

There are six main sand-mud bed couplets within the reservoir-fill section; these are interpreted as depositional cycles, an idealized example of which begins just above 1120 m (cycle 3; Figs. 4 and 5A,B): The sharp basal contact of planar-bedded fine sand transitioning upward to climbing ripples represents discharge and water level rise, followed by a transition to stacked oscillatory ripples at the top of the sand as discharge falls but reservoir level continues to rise, resulting in a gradational contact with lacustrine mud as reservoir level maintains elevation and sand deposition ceases. Eventually, as reservoir level decreases, the muds are exposed and subject to colonization by tamarisk and other vegetation, with some roots extending into the underlying sands (Fig. 5E). This represents a period of non-deposition (unconformity) before the next depositional cycle begins (i.e., sharp contact with overlying sand unit just below $\sim$1122 m, Fig. 4). Thus, the depositional cycles reflect seasonal fluctuations in reservoir elevation, followed by much longer periods of non-deposition (Miall, 2014).

The broader chronostratigraphic interpretation of the Calf Canyon section hinges on reservoir level history, with preliminary interpreted timeline correlations indicated on Fig. 4. Known highstands that would have extended to the elevation of Calf Canyon occurred between 1975 and 2000 (Fig. 2B). Between 1983–1990, the reservoir remained above the lowermost sediment elevation. It is likely that the bulk of reservoir sediment in Calf Canyon was deposited during this period, with sand-mud couplets being controlled by the interplay between annual cycles of discharge and reservoir level. After 1995, the reservoir level and uppermost sediment elevation were approximately coequal, with spring runoff floods possibly providing a mechanism to deposit the uppermost reservoir sediment.

By this interpretation (Fig. 4), the 12 m of reservoir sediment in Calf Canyon was deposited in $\sim$15 years of highstands (1975–1977, 1980–1988, 1995–2000), with $\sim$10 years completely missing from the sedimentary record at this site during lowstands. Deposition was certainly not continuous within the highstand phases; the majority of stratigraphic thickness is comprised of sand beds interpreted to represent river flood-stage deposition during rising base level.

DISCUSSION

Stratigraphic controls and signals

There are six stratigraphically distinct lake beds in the Calf Canyon section. Assuming an elevation threshold of 1118 m, there are 17 reservoir level highstands during which accumulation of lacustrine sediment could have occurred. If an elevation threshold of 1128 m is considered, there are six highstands, all between 1980–1988, when lacustrine deposition at Calf Canyon could have occurred (Fig. 4). In every instance, these elevation thresholds are crossed for only months, because the duration of these highstands was controlled by seasonal reservoir water-storage cycles. If sand deposition was synchronous with Colorado River floods when the reservoir was already high, these thresholds were even briefer. Without subdividing mud units based upon subtle subaerial exposure features, the correlation of reservoir elevation record to the stratigraphy solely by counting lacustrine beds is not straightforward. It is possible that some of the lower mud units are composites of multiple annual cycles during the mid-1980s and thus some of the sand-mud couplets may represent a few annual cycles at maximum highstand. In particular, prior to the 1983 Colorado River flood, the lower parts of Calf Canyon may have remained inundated through the fall and winter. Rather than try to correlate discrete mud beds to specific annual highstands through the 1980s, we group this interval into cycles 2–5. Further, our stratigraphic analysis relies on additional observations to interpret reservoir level controls on sedimentation and explore linkages with the instrumental record.

Our preferred interpretation is that the lowermost lacustrine bed (Fig. 4, cycle 1) was deposited during the initial flooding of Calf Canyon in 1975–1976. The sharp rise in reservoir level beginning in spring 1979 certainly flooded Calf Canyon and resulted in deposition of fine-

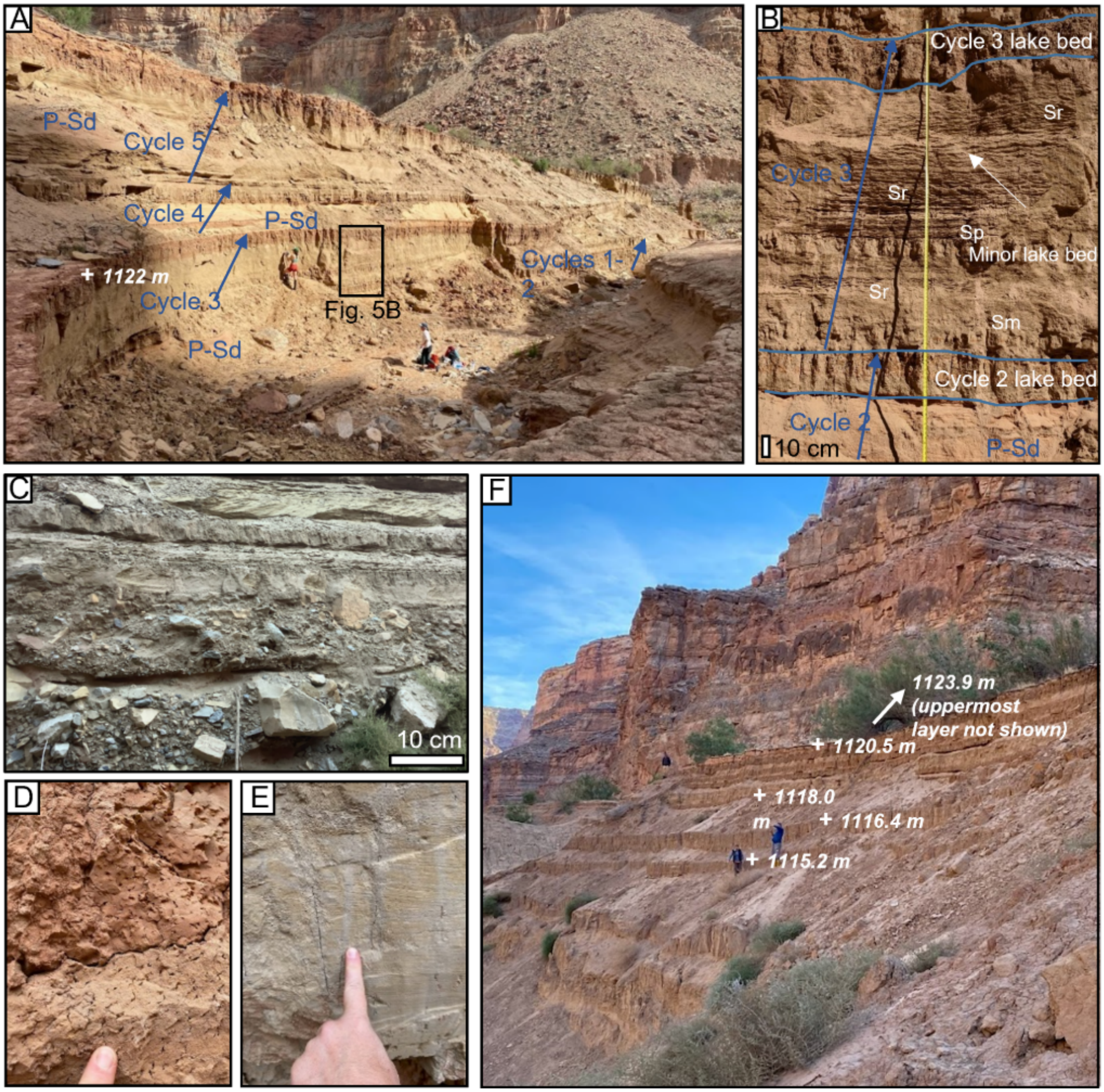

Figure 5: (A) Overview of lower Calf Canyon section from the top of Cycle 3 (1122 m as marked with "+"), cf. Fig. 4). P-Sd denotes pink sands. (B) Detailed view of cycles 2 and 3 (location shown in Fig. 5A; cf. Fig. 4). The main sand bed in cycle 3 shows massive (Sm) to planar lamination (Sp) and thick climbing ripple cross lamination (Sr). The white arrow indicates a steep climbing angle (likely supercritical, with both stoss and lee sides preserved) towards the left, which is up Calf Canyon and away from the mainstem Colorado River. (C) Poorly sorted, matrix-supported cobble-boulder beds at the base of Calf Canyon. These beds are interpreted as debris flow deposits which are overlain and onlapped by the lowermost reservoir sediment layers (cycles 1–2; cf. Fig. 4). (D) Characteristic expression of blocky pedogenic textures in muds interpreted to be lake bed deposits. Pockmarks are oxidized and suggest vegetation-induced sedimentary structures. (E) Tamarisk rootlets extending from a lake bed into its underlying sand bed, indicating prolonged exposure and colonization (Cycle 5, Fig. 4). (F) Reservoir sediment exposed along the Colorado River at "Best Western" campsite (37.95198, -110.18890), ~18 river-km downriver from Calf Canyon (Fig. 1). Several sand-mud cycles form ledges within this section, which is more than 20 m thick ("+" denotes RTK-measured elevation in m above NAVD 88 for the middle and upper units). Similar sections of reservoir sediment are semi-continuously exposed for >50 km in the reservoir affected zone of the Colorado River, as well as in other major Lake Powell tributaries (Fig. 1).

grained sediment derived from the Colorado River. Historical photos from April 1980 confirm that the top of the stratigraphic section was inundated by the reservoir by that time (Fig. 3D,E). How much of the stratigraphic section to attribute to the first two transgressive episodes is unclear, but the discharge peaks of the late 1970s and early 1980s are believed to result in significant sediment flux (Fig. 4, cycles 2–5).

Interpretations of discharge-driven sediment flux and deposition are supported by the thick beds of fine-grained sand. That these sands include distinctive detrital minerals such as white mica points to a mainstem Colorado River sediment source. Furthermore, a high rate of sediment accumulation can be inferred from the meters-thick sequences of climbing ripple cross lamination preserved between 1120–1126 m (cycles 2–5). These phases of rapid sedimentation could have occurred over periods of hours to days (cf. Ashley et al., 1982; Jobe et al., 2012). Thick climbing ripple expressions with common up-canyon migration directions suggests waning flood stage deposition in an eddy within this embayment (Benito et al., 2003).

A reasonable analogy can be drawn to the results from a sediment trap deployment in the North Wash embayment, near Hite, for the duration of the 1975 spring runoff (Anderson, 1977). During this study, the embayment was both larger and further from the river-mouth delta as compared to Calf Canyon, but correlations between both Colorado River discharge and sediment load and North Wash sedimentation rate are robustly documented. Given that Lake Powell typically has its lowest levels in March and April just prior to spring runoff, which in turn drives water level rise, discharge-driven depositional cycles could be predicted to result in sand/mud couplets as expressed in Calf Canyon. These couplets can be interpreted to represent an annual reservoir water-storage cycle, especially for the high inflow years of the mid-1980s (Fig. 4, cycles 2–5). As such, the majority of the stratigraphic section could be inferred to result from a few high discharge years, an interpretation we prefer from the basal contact of the sand just above 1120 m through the top of the penultimate lacustrine bed just above 1127 m (Fig. 4, cycle 6). Further, these couplets might reasonably represent only April–October deposition in a given year depending on the interplay between inflow and reservoir management, which typically leads to variations in reservoir level similar to the sediment thickness at Calf Canyon (average of 7.8 ± 3.7 m for the period 1975–2000, max = 17.6 m annual variation). As previously noted, a multi-year mud bed is a possible interpretation for a restricted set of years; however, in the absence of significant evidence for this, the annual cycling of discharge and reservoir level suggest that most mud beds are interpreted to represent a single annual cycle separated by discharge-driven mainstem sand deposition.

The nature of the sharp basal contacts of sand beds on underlying lacustrine mud provides a final line of evidence in the stratigraphic interpretation of the Calf Canyon section. Importantly, pedogenic features are present throughout lacustrine beds but are particularly well developed near their upper contacts (Fig. 5D,E). In addition to their blocky oxidized nature, many of the upper contacts have evidence of rooting. Rooting features are particularly evident at 1119 and 1127 m and in the case of the latter rooting zone tamarisk plants containing multiple years of growth originated at this horizon. While evidence of subaerial exposure was observed in every lacustrine bed, these surfaces have not been exhaustively documented, and other cryptic surfaces may exist within the studied section. Nonetheless, their importance to stratigraphic interpretation is clear, and we focused on the 1119 and 1127 m levels as representing multi-year exposure events during which the annual reservoir water-storage cycle did not impact sedimentation at Calf Canyon. We tentatively ascribe the 1119 m level to the 1977–1978 lowstand, and the 1127 m level to the 1989–1995 lowstand (Fig. 4).

One implication of this depositional model is that the river-mouth 'shoreline' would have passed by or very close to Calf Canyon several times, prior to deposition of the lake beds and many times during accumulation of the sand-mud couplets. The present-day expressions of this migrating shoreline are the deltas of the Colorado, Escalante, Dirty Devil, and San Juan Rivers (Vernieu, 1997; Pratson et al., 2008). These deltas are highly mobile, and progradational rather than truly distributive, due to confinement by canyon walls. As a result, they are sensitive to short-term variations in discharge, sediment flux, and base level, with the latter only temporarily inundating prograding deltas on an approximately annual basis. We cannot discount some degree of delta-influenced sedimentation in the Calf Canyon section, however, the cyclic packaging implies rapid annual high/low fluctuations within a decadal high-stand period, rather than prolonged stability of a deltaic 'shoreline' at this location.

The prevalence of pink sands in the upper section may also be related to base level controls, specifically lowstands. The pink sands, with iron-oxide stained quartz grains, are interpreted to source from the side drainage above the canyon rim and to pour over the rim with a transport direction towards the Colorado River. No sedimentary structures with clear evidence for paleoflow were observed in these units, but the presence of minor pebble and gravel lags increased both up-section and towards the pour-over at the head of Calf Canyon. Deposition of the pink sands is interpreted to represent localized precipitation events that transported material down Calf Canyon; however, their admixture with mainstem sediment, plus laterally extensive deposition and preservation is likely favored during lowstand conditions.

The fact that there is no obvious cut-and-fill stratigraphy in the reservoir sediment of Calf Canyon suggests that incision through the reservoir sediment, and resultant exposures in its present-day form, likely resulted from a single period of incision between 1998 (abandonment of lake deposition at this elevation) and ∼2015, where photos show essentially present-day canyon morphology (Fig. 3B). Thus, reservoir sediment was mainly deposited during transgressive and highstand phases of reservoir level between 1975–2000, strongly modulated by mainstem river discharge and episodic side canyon flash flood events driven by local precipitation. The highest modeled reservoir elevation, approximately 1132 m in 1983, is expressed by a high-water mark in Calf Canyon that coincides with the physical extent of tamarisk and abandoned driftwood (Fig. 3B). The only evidence of the prolonged lowstand since 2000 is erosion and exposure of reservoir sediment combined with alluvial and talus slope gully deposits.

Implications for regional anthropogenic stratigraphy

Impoundment of Lake Powell tributaries dramatically impacted hundreds of river-km along the Colorado, San Juan, Escalante, and Dirty Devil Rivers, an area up to 650 km^2 (Ferrari, 1988; Root & Jones, 2022). Observations up and down river from Calf Canyon indicate that this location is particularly sensitive to high reservoir levels: 2.5 km upstream at Imperial Canyon (Fig. 1) only ∼2 thin, poorly exposed lacustrine mud units exist within an alluvial dominated package of reservoir sediment. However, reservoir sediment in Cataract Canyon downriver of Calf Canyon is notably both thick and laterally extensive, including multiple m-scale mud beds exposed along the Colorado River for more than 50 km, with many sites preserving 10s of meters of interbedded sand, silt, and mud (cf. Fig. 5F). Stratigraphic sections lower in the reservoir have a higher likelihood of containing composite (multi-annual) mud beds, and sand-mud couplets may represent a response to base level at multi-annual scales depending on location. Observations and preliminary mapping from the other major tributaries (Fig. 1) indicate that there are significant, analogous sedimentary archives regionally throughout the reservoir-affected zone.

It is possible that the lacustrine marker beds surveyed at Calf Canyon and interpreted here in a chronostratigraphic framework of known highstands will have downriver equivalents that can be correlated directly. However, the true significance of this reference section is its basis as a depositional model which highlights interplay between three main signals: (1) periods of lacustrine deposition controlled mainly by reservoir operations, and pedogenic modification during subsequent exposure; (2) flux of mainstem river sand into side canyons during Colorado River floods; and (3) local tributary-sourced sand and gravel deposition, linked to tributary flash floods. We predict that similar sedimentary processes are present elsewhere in zones of the reservoir with high sedimentation rates (i.e. river-reservoir interface), albeit with variable sedimentologic and stratigraphic expressions. Variations are expected given local differences in tributary source areas, canyon morphology, and base level fluctuations, as well as sedimentary processes not specifically discussed here (eolian processes, slumping, turbidity currents, distal lacustrine sedimentation, etc.).

Reservoir sediment, particularly thick fluvial-lacustrine deposits, are a global phenomenon deserving of detailed study (e.g., Stratton & Grant, 2019). Such deposits are striking testimony to the impact of humans as geologic agents (cf. Hooke, 2000; Crutzen, 2016; Wilkinson, 2005; Wilkinson & McElroy, 2007). This notion is emblematic of reservoirs in the western United States, where damming of continental scale drainages combined with climate change and prolonged drought has resulted in major reservoirs at all-time lows and concomitant exposure of vast areas of anthropogenic sediment. Future streamflow in the southwestern United States is projected to decline in response to climate change (Milly & Dunne, 2020), and current water use already exceeds availability despite a predicted increase in demand (Miller et al., 2016; Miller, Miller, et al., 2021). Baseflow in the Upper Colorado River Basin is expected to face a significant decline in the near future (Miller, Putman, et al., 2021), and the influence of a declining baseflow on water quality, such as salinity (Rumsey et al., 2017, 2021), is not understood. Similarly, the fate of reservoir sediment under further drawdown conditions, including potential remobilization of large volumes of fine-grained sediment, and implications for solute, contaminant, and nutrient transport (e.g., Wildman et al., 2011; Wildman & Hering, 2011; Frederick et al., 2019; Deemer et al., 2020), pose significant concerns and highlight the need for further study of this and analogous sedimentary records of anthropogenic activity.

CONCLUSIONS

Construction of Glen Canyon Dam marked the beginning of a decades-long, basin-scale controlled experiment in the Upper Colorado River Basin. The prolonged recession of Lake Powell since 2000 yielded a lowstand from 2003–2005, and even lower reservoir elevations since summer 2021. Resultant exposure of fluvial-lacustrine deposits complemented by an excellent instrumental record provides a unique opportunity for sedimentologic and stratigraphic analysis. A comprehensive record of reservoir elevation, inflow, and suspended sediment load exists for important sites in the UCRB since the early 1900s. The hydrologic and sedimentologic records prior to major impoundments in the watershed are contextually important in understanding the abrupt transition to anthropogenic sedimentation. The complex overlay of climatic factors ranging from regional drought conditions to decadal, annual, and seasonal signals (i.e., spring runoff and monsoon intensity) are further complicated by reservoir management; however, the local base level as controlled by dam release is documented by a daily reservoir level record for the entirety of Lake Powell's history. As a result of this rich instrumental and geospatial record, there are few places in the world where better constraints exist on the initial transition from an open fluvial basin to a closed and fluctuating lacustrine basin (Carroll & Bohacs, 1999).

With these exceptional records available, as well as regionally extensive reservoir sediment emerging due to drought conditions and reservoir drawdown, there is a unique opportunity to test fundamental concepts of sequence stratigraphy in the context of significant societal and environmental impacts. This study is an initial step towards these goals, and it demonstrates that the stratigraphic record of reservoir sedimentation can be linked to both reservoir level and river discharge records with reasonable confidence. Results show that sedimentation at Calf Canyon mainly occurred in discrete time intervals linked to high spring runoff, and subsequently rising reservoir base level. These annual cycles underpin a depositional model, but partitioning of sediment accumulation between decade scale transgressive and highstand phases is less certain. There are also distinct petrofacies representing side-canyon tributary derived sediment versus deposits supplied by the mainstem Colorado River. Investigations could readily be made into sediment volume partitioning, signal preservation (e.g., short- and long-term signals and reservoir level versus discharge controls), and effects of reservoir management on sedimentation. An especially important role for the field of sedimentary geoscience is the coupling of sediment and water fluxes in various combinations of hydroclimatic and management scenarios. Sediment in large reservoirs will need increasingly sophisticated management as infrastructure ages. Regardless of management strategy, reservoir sediment will become a long-lived archive of recent Earth history, and has the potential to become a focal point for scientific and societal discussions regarding human impact on Earth surface processes.

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