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Pleistocene Colorado River terraces in the canyonlands region (Utah, USA) record unsteady, transient incision and growth of the Cataract Canyon knickzone by salt tectonics

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ABSTRACT

Colorado River terraces in the canyonlands region of southeastern Utah can be dated and analyzed to address the controls of incision and nature of the Colorado Plateau's largest channel-steepness anomaly, Cataract Canyon. Field correlations supported by luminescence and cosmogenic-nuclide ages on strath terraces along Meander Canyon, upstream of Cataract Canyon, reveal a complex record of unsteady incision over the past ~340 k.y. at an average rate of ~0.4 mm/yr. Both an upstream progression of rapid incision and a unique sigmoidal long-profile pattern of terraces indicate incision in response to episodic baselevel fall. Also, terraces converge downstream with the anomalously low-gradient modern channel above Cataract Canyon. We interpret these results as indicating that growth of the Cataract Canyon knickzone is due to an erosion-salt tectonics feedback since at least the Mid Pleistocene, which has imparted unsteady, and currently elevated, local baselevel. More broadly, the canyonlands region is marked by rapid and unsteady incision that is complicated by local geologic controls even while being absent of any regional or mantle-driven uplift.

INTRODUCTION

The evolution and geodynamics of the Colorado Plateau (southwestern United States) landscape are subjects of persistent debate as part of a broader effort to understand the uplift and exhumation of orogenic plateaus. Data sets on the incision patterns of the Colorado River, the baselevel in the Colorado Plateau, have been used to support two conceptual models of regional landscape evolution: steady but spatially varying incision rates driven by dynamic-mantle uplift (Crow et al., 2014; Karlstrom et al., 2017; Walk et al., 2019), versus unsteady and transient incision due to baselevel changes and local geomorphic controls (Wolkowinsky and Granger, 2004; Cook et al., 2009; Darling et al., 2012; Jochems and Pederson, 2015). Geographically central to this debate is the canyonlands region, including the low-gradient Meander Canyon and the Cataract Canyon knickzone on the Colorado River (Fig. 1).

Researchers advocating for transient incision highlight that the integration of the Colorado River off the plateau at ca. 4.6 Ma initiated the ~1.5 km baselevel fall, driving deep incision of Grand Canyon (Lucchitta, 1972; Crow et al., 2021) and ongoing incision upstream (Pederson, 2008; Cook et al., 2009; Abbott et al., 2015). Thermochronology in the central Colorado Plateau indicates the onset of >2 km of exhumation in the Pliocene–Pleistocene (Murray et al., 2016, 2019). Tracking the migration of this baselevel-fall signal through the Colorado River system is complex due to the superimposed effects of variable rock strength, erosion-driven isostatic rebound, dynamic mantle processes, and salt tectonics (Kirkham and Scott, 2002; Darling et al., 2012; Karlstrom et al., 2012; Pederson et al., 2013b; Bursztyn et al., 2015; Jochems and Pederson, 2015). Researchers promoting a steady-state model suggest that long-term incision rates are steady, with spatial differences correlating to underlying mantle velocity gradients along the margins of the plateau (Karlstrom et al., 2012, 2017; Walk et al., 2019). However, in the central Colorado Plateau, there is no evidence of mantle anomalies (Moucha et al., 2009; Karlstrom et al., 2022).

We used river terraces to investigate regional landscape evolution, filling a data gap in the canyonlands region of the central Colorado Plateau (Fig. 1). The Colorado River first flows through the low-gradient Meander Canyon and then (~5 km downstream of the Green River confluence) through the Cataract Canyon knickzone, the greatest channel steepness anomaly along the Colorado River profile (Pederson and Tressler, 2012). The Cataract knickzone is spatially coincident with exposure of the Paradox Formation or salt diapirs rising from it, where unloading by river incision potentially initiated the collapse of topography and ductile salt flow in an ongoing feedback (Huntoon, 1982; Furuya et al., 2007; Kravitz et al., 2017). We surveyed and dated the preserved record of Colorado River terraces, mostly along ~100 km of Meander Canyon. Our results indicate unsteady and transient river incision, which we interpret as linked to salt diapirism and the building of the Cataract knickzone in the Mid- to Late Pleistocene.

THE CATARACT ANOMALY

There is an intriguing contrast in geomorphology between Meander and Cataract Canyons in Canyonlands National Park (Fig. 1). Through Meander Canyon, the Colorado River flows at an unusually low gradient (0.2 m/km) in a broad and sinuous canyon. At its downstream end, it follows a salt-flow–generated river anticline of increasing amplitude as the canyon cuts lower stratigraphic levels (Huntoon, 1982). At the knickpoint and first emergent salt diapir of Cataract Canyon, the gradient sharply increases tenfold to 2.1 m/km. Salt diapirs in Cataract exist where tributary mouths locally widen the river corridor (Huntoon, 1982; Kravitz et al., 2017). The canyon walls of Cataract are highly

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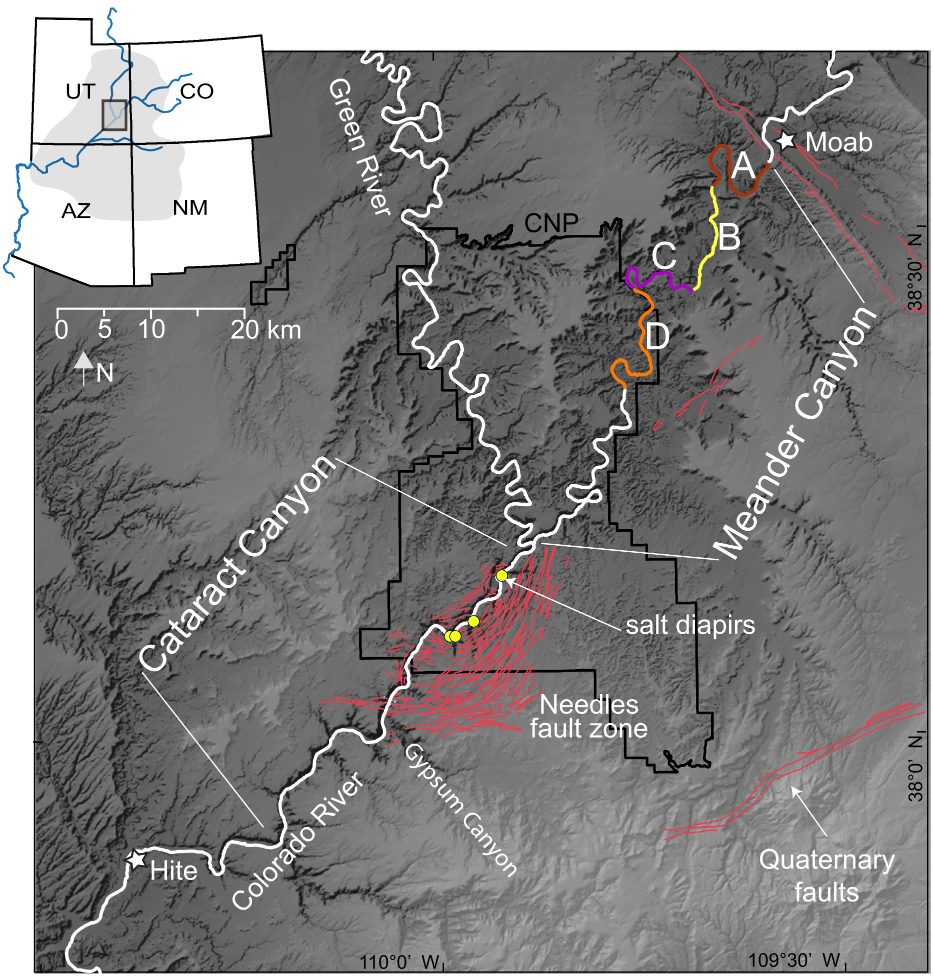

Figure 1. Canyonlands region of the central Colorado Plateau, southwestern USA, depicting key locations in this study. Reaches A–D of the Colorado River in Meander Canyon correspond to the cross-section reaches in Figure 2. Quaternary faults (red) are from the U.S. Geological Survey Fault and Fold Database (https://earthquake.usgs.gov/cfusion/qfault/query_main_AB.cfm). CNP—Canyonlands National Park; AZ—Arizona; CO—Colorado; NM—New Mexico; UT—Utah.

fractured, and there is a clear increase in mass-wasting processes delivering coarse sediment to the river (Webb et al., 2004). Exhumation of the canyon corridor has permitted the break-up and lateral spread of the brittle rocks overlying the evaporites, creating the Needles fault zone (Fig. 1; Mcgill and Stromquist, 1975). The onset of rapid incision of Cataract Canyon, and therefore initiation of salt tectonics, has been broadly estimated at 0.2–1.0 Ma (Mcgill and Stromquist, 1975; Geiger, 2014) consistent with a Mid-Pleistocene increase in incision rate observed both downstream and upstream (Darling et al., 2012; Mauch, 2018).

The controls on knickzone formation in Cataract Canyon need to be investigated. Knickzones can form due to transient incision (Crosby and Whipple, 2006), stable adjustments to locally higher rock-uplift rate (Burbank et al., 1996), more resistant bedrock (Bursztyn et al., 2015), or coarse sediment input (Finnegan et al., 2017). An increase in bedrock resistance or change in tectonics cannot explain the gradient change in Cataract Canyon, as the strata exposed in Cataract and the lower 25 km of Meander canyons are the same and there are no active faults or orogen-scale tectonics in either canyon. Instead, this geomorphic change has two potential explanations. First, in Meander Canyon and the analogous lower reaches of the Green River, Webb et al. (2004) observed that terraces seem to gradually decrease in height above the river downstream and project below grade and hypothesized that upstream reaches aggraded behind a dam of mass-movement debris due to a stormier climate increasing sediment supply in the Holocene. This hypothesis is inspired by the links between debris fans and steep gradients in the region (Grams and Schmidt, 1999) and by a record of >34 m of alluvial fill below the channel at the confluence of the Colorado and Green Rivers (U.S. Bureau of Reclamation, 1922).

A second hypothesis is that local baselevel rise and rock fracturing and mass wasting due to salt tectonics has developed the knickzone over a longer period than the Holocene. Supporting this is interferometric synthetic aperture radar (InSAR) analysis, indicating that salt-related deformation is active and generating 2–3 mm/yr of uplift along the canyon floor (Furuya et al., 2007), while numerical modeling of the salt system predicts even higher rates (Kravitz et al., 2017).

METHODS

Pleistocene fluvial terraces are well preserved in upper Meander Canyon, rare in the lower reaches, and absent through Cataract Canyon until near its end, at Gypsum Canyon. We mapped and GPS-surveyed all preserved Pleistocene terraces along Meander and at the mouth of Gypsum canyons to document treads, straths, and geochronology samples (Figs. 2 and 3). Terraces were correlated in the field, and chronology provided by 20 luminescence ages and one ^{26}Al/^{10}Be terrestrial cosmogenic nuclide (TCN) exposure-profile (Table 1) confirm the field interpretations. We collected luminescence samples from sand lenses, typically ~30 cm thick, with intact sedimentary structures. TCN samples were obtained from an excavation in the tread of a 100-m-high terrace deposit central to the study area, which is cross-dated by luminescence techniques. See the Supplemental Material[1] for details on the dating methods.

RIVER TERRACE CORRELATION, CHRONOLOGY, AND PATTERNS

Fluvial terraces (T) through Meander Canyon range from 5 m (T3) to 156 m (T11) above the water surface of the modern river (Fig. 2). Bedrock and canyon topography change between reaches, controlling terrace preservation. Meander Canyon begins as a 230-m-deep, steep-walled canyon within Jurassic sandstones (reach A in Figure 1) and cuts through older strata downstream. The canyon is widest and has abundant terraces in reach B, becoming stairstep in cross section through sandstones and mudstones of the Cutler Group. In reaches C and D, an inner canyon develops where interbedded limestones of the lower Cutler beds form cliffs. Downstream of reach D, a 300-m-deep, narrow canyon develops with no terraces as it incises into the resistant limestones of the Honaker Trail Formation. Field photos illustrate these patterns (Fig. S7 in the Supplemental Material).

Pleistocene terrace deposits in Meander Canyon are generally 2–5 m thick above a relatively planar bedrock strath. Deposits are clast-supported, broadly lenticular bedded, imbricated,

[1]Supplemental Material. Details on luminescence dating, TCN exposure age, measurement of canyon width, conceptual model of transient incision, and field photos. Please visit https://doi.org/10.1130/GEOL.S.24525808 to access the supplemental material; contact editing@geosociety.org with any questions.

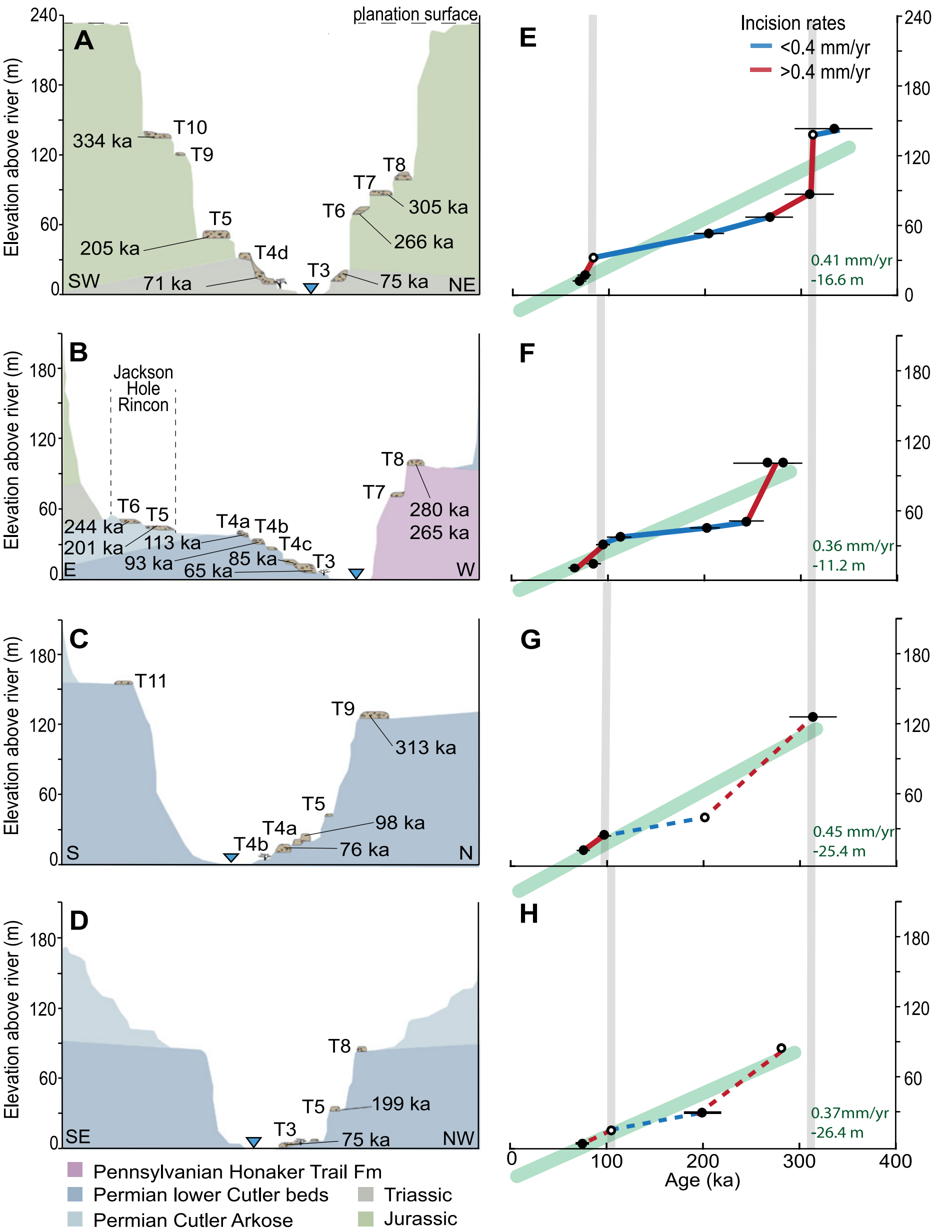

Figure 2. (A–D) Schematic profiles representative of terrace stratigraphy in reaches A–D of the Colorado River in Meander Canyon, Utah (Fig. 1), with central age results for deposits. Fm—Formation. (E–H) Plots of reconstructed Colorado River grade through time (dashed where inferred), constrained by luminescence ages (black circles) with bars representing reported error or terrace ages from other reaches projected to that reach based on correlations in Figure 3A (open cirlces). Green lines are linear regressions for the overall incision rate, with projected modern depth reported in the lower right. Vertical gray lines show the onset of both rapid incision phases.

rounded, pebble-cobble gravel, with rare sand lenses. Some gravels are capped by <5 m of locally preserved channel-margin and overbank sand. In contrast, alluvium is preserved at the mouth of Gypsum Canyon as thick fill terraces with straths that are mostly below grade.

Correlation of the terraces in long-profile confirms Webb et al.'s (2004) hypothesis that they are not parallel to the modern channel and instead have higher gradients and generally converge downstream (Fig. 3A). The T3 and T5, and potentially the T8 and T9, terraces are parallel to each other, whereas a suite of T4 terraces that can be traced in the field through reaches A and B exhibit a distinct sigmoidal pattern in long-profile, consistent with a transient knickzone (Fig. 3A; Fig. S6). The higher terraces of reach A include a profusion of remnants around the T7 level that are difficult to correlate (Fig. 3A). We hypothesize that these represent an older transient sequence like the T4 suite.

Luminescence ages span 50 ka to 340 ka, providing the most comprehensive chronostratigraphy of Mid- to Late Pleistocene fluvial deposits along the Colorado River (Table 1). The most prominent Pleistocene terraces with multiple geochronologic constraints are the T5 at ~200 ka, the T4 suite at ~110–80 ka, and T3 at ~75–65 ka (Fig. 2), whereas higher Mid-Pleistocene terraces are less-continuously preserved and have fewer age constraints.

The T8 has a luminescence age of 280 ± 21 ka and a modeled TCN exposure-profile age of 265 ± 34 ka (Fig. 2B). The Late Pleistocene T4 suites are geometrically complex and include four intermediary terrace levels (T4a–T4d) that we interpret as more-frequent terrace abandonments that luminescence precision cannot capture. The overall T3 and T4 suite ages correspond with other terrace deposits studied in the region (Pederson et al., 2013a, 2013b; Jochems and Pederson, 2015), implying a common climate driver for terrace formation. Yet, only in Meander Canyon are these deposits the lowest terraces in the landscape, with multiple inset treads and deposits developed in the same time span as singular terrace deposits elsewhere. Regionally, the youngest terrace (T2) dates to the Marine Isotope Stage 2, and it is prominent ~35 km upstream along the Colorado River (Jochems and Pederson, 2015). Yet, this deposit is not exposed within our study area, and we hypothesize that these deposits were once present but are now buried (Fig. 3B).

Incision rates between terraces for each reach of Meander Canyon are unsteady over the time of our record but produce long-term incision rates of ~0.4 mm/yr at all locations (Figs. 2E–2H). There appears to be two pulses of rapid incision recorded in each reach, with an intervening episode of slow incision over T6 to T4a time from ca. 250 ka to 110 ka. The onset of the most recent pulse of incision potentially becomes younger in the upstream direction from ca. 110 ka to 70 ka. This upstream progression of rapid incision follows the expected pattern of transient incision as illustrated in Figure S6. Projection of the average rate in each reach predicts that current alluvium-bedrock contacts are increasingly farther below grade approaching Cataract Canyon (Figs. 2E–2H), reflecting recent aggradation.

DISCUSSION

The Colorado River terrace record in Meander Canyon documents rapid but unsteady incision through the Mid- to Late Pleistocene, interpreted here as reflecting a complex history of baselevel and geomorphic feedbacks tied to salt tectonics downstream in Cataract Canyon. Alternate controls on these patterns must also be considered. First, the incision rates show no "Sadler effect" of being systematically dependent on time intervals and are calculated across time intervals longer than the Pleistocene glacial cycles (Gallen et al., 2015; Fig. 2B). To address potential bedrock controls, we conducted an

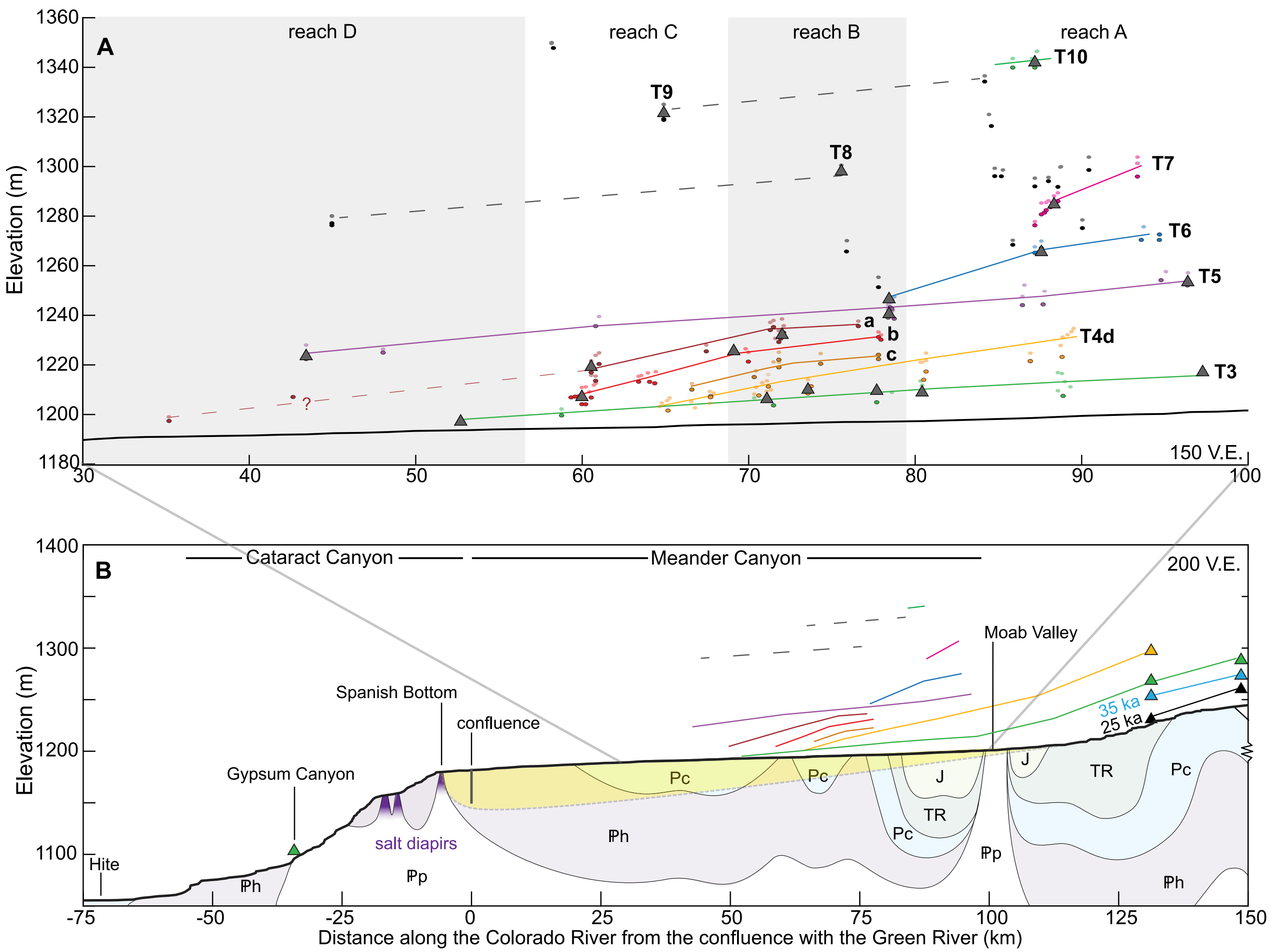

Figure 3. Longitudinal profile of the Colorado River through Meander Canyon, Utah (A), and from Dewey to Hite, Utah (B), with terrace correlations (lines, dashed where inferred), terrace straths (solid dots), treads (opaque dots), and sample locations (triangles). (B) Bedrock geology is shown in cross section below the profile, including alluvium depth at the Green River–Colorado River confluence and inferred alluvium depth (yellow) in Meander Canyon. Triangles upstream of Moab refer to chronostratigraphic records from Jochems and Pederson (2015). V.E.—vertical exaggeration; ₽p—Pennsylvanian Paradox Formation; ₽h—Pennsylvanian Honaker Trail Formation; Pc—Permian Cutler Formation; TR—Triassic; J—Jurassic.

analysis of canyon width and geometry as a function of bedrock units (Fig. S5). The canyon bottom in Meander Canyon is systematically ~105 m wider than in reaches upstream that pass through the same geologic units, while still retaining the relative width patterns between those bedrock groups (Fig. S5D). The systematically wider floor of Meander Canyon is consistent with recent aggradation in response to local baselevel rise in Cataract Canyon.

Our terrace record captures two episodes of rapid incision since ca. 315 ka separated by a reduction of incision rates to < 0.2 mm/yr from ca. 250 ka to 110 ka. The subsequent phase of rapid, transient incision marked by the T4 suite indicates a pulse of baselevel fall from ca. 110 ka to 60 ka or after. Evidence for Late Pleistocene transient incision continues upstream above Moab, Utah, where fluvial terraces record increasingly rapid incision over the past ~60 k.y. (Fig. 3B; Jochems and Pederson, 2015). This is consistent with expectations of more rapid and younger incision upstream under transient incision (Fig. S6).

The terrace record and canyon geometry of Meander Canyon is key to understanding the formation of the Cataract Canyon knickzone. The modern gradient in Meander Canyon is anomalously low, with Pleistocene terraces projecting below grade above Cataract Canyon and no terraces preserved through it until Gypsum Canyon, downstream of the salt-tectonic influence (Fig. 3B). Although Webb et al.'s (2004) proposed Holocene sediment deluge in Cataract would contribute to a high gradient there, our terrace record upstream indicates that unsteady local baselevel has been the norm for 300 k.y. or more, with the most recent baselevel rise in Cataract Canyon sometime after ca. 60 ka. Therefore, we suggest the Cataract knickzone formed due to halokenesis, with salt-related deformation driving enhanced mass wasting in a feedback ultimately triggered by renewed incision in the Mid-Pleistocene. The modern long profile is consistent with this idea, as the knickzone begins exactly at the first emergent and uplifting salt diapir (Kravitz et al., 2017; Fig. 3B). Contrasting with this present condition, we suggest Pleistocene pulses of incision were caused by episodes of reduced diapirsm and/or by the Colorado River reaching a steepness threshold that drove incision within Cataract Canyon.

Our results from the canyonlands region of the central Colorado Plateau signify that local processes are dictating complex, transient patterns of incision. The slow-velocity and static mantle lithosphere beneath the central Colorado Plateau cannot produce the observed patterns of unsteady incision. Instead, downstream base-

TABLE 1. CANYONLANDS GEOCHRONOLOGY

(A) Luminescence Age Information

USU number	Elevation (m)	Deposit*	Depth (m)	Location (NAD 83) Lat (°N)	Long (°W)	Number of aliquots†	Dose rate (Gy/kyr)§	OSL/ IRSL#	Fading Rate g_{2days} (%/decade)#	Equivalent Dose ± 2σ (Gy) **	Age ± 1σ (ka)
Reach A											
USU-2796	1209	T3	1.5	38.5367	–109.6524	10 (12)	3.51 ± 0.19	IRSL	2.8 ± 0.3 (n = 7)	249.7 ± 27.3	71.0 ± 6.0
USU-3611	1216	T3	0.8	38.5603	–109.5867	10 (17)	3.39 ± 0.19	IRSL	3.9 ± 0.6 (n = 6)	255.2 ± 25.0	75.2 ± 6.0
USU-3385	1253	T5	4.2	38.5513	–109.5891	9 (15)	3.48 ± 0.19	IRSL	2.6 ± 0.2 (n = 7)	714.4 ± 70.7	205.2 ± 15.1
USU-3731	1266	T6	2.0	38.5756	–109.6312	9 (16)	3.69 ± 0.19	pIR^{250}-IRSL	1.9 ± 0.3 (n = 6)	979.3 ± 133.6	265.5 ± 24.7
USU-3386	1285	T7	5.0	38.5626	–109.6300	10 (14)	3.81 ± 0.20	IRSL	2.0 ± 0.2 (n = 10)	1160.6 ± 124.0	304.9 ± 25.2
USU-3506	1342	T10	4.5	38.5717	–109.6420	13 (19)	4.03 ± 0.20	IRSL	3.1 ± 0.5 (n = 7)	1343.9 ± 279.2	333.8 ± 40.5
Reach B											
USU-3282	1206	T3	1.5	38.4602	–109.6692	15 (19)	2.81 ± 0.08	OSL	–	182.3 ± 21.5	65.0 ± 4.7
USU-2667	1210	T3	1.3	38.5126	–109.6542	10 (15)	3.68 ± 0.21	IRSL	2.7 ± 0.8 (n = 5)	233.9 ± 17.6	63.6 ± 5.2
USU-2415	1211	T4d	2.5	38.4766	–109.6520	10 (14)	3.42 ± 0.21	IRSL	3.5 ± 0.8 (n = 5)	290.1 ± 29.9	84.8 ± 6.4
USU-3283	1226	T4b	2.0	38.4401	–109.6722	15 (24)	2.93 ± 0.08	OSL	–	273.8 ± 27.0	93.5 ± 6.0
USU-3508	1233	T4a	6.0	38.4665	–109.6650	10 (18)	3.46 ± 0.19	IRSL	2.5 ± 0.2 (n = 7)	389.3 ± 68.6	112.6 ± 12.2
USU-2411	1243	T5	3.5	38.5122	–109.6299	11 (13)	4.79 ± 0.24	pIR^{250}-IRSL	2.4 ± 0.2 (n = 3)	963.9 ± 82.2	201.4 ± 15.3
USU-2413	1247	T6	2.3	38.5137	–109.6295	10 (11)	4.10 ± 0.22	pIR^{250}-IRSL	2.1 ± 0.5 (n = 4)	999.4 ± 75.3	243.8 ± 18.0
USU-2544	1298	T8	1.8	38.4958	–109.6535	10 (16)	4.37 ± 0.22	pIR^{250}-IRSL	2.3 ± 0.4 (n = 7)	1224.9 ± 102.5	280.3 ± 21.2
Reach C											
USU-3286	1208	T4b	4.0	38.4430	–109.7453	16 (26)	2.15 ± 0.06	OSL	–	163.6 ± 9.8	76.1 ± 3.8
USU-3284	1220	T4a	2.5	38.4446	–109.7414	15 (18)	2.41 ± 0.06	OSL	–	236.2 ± 23.2	98.1 ± 6.3
USU-3610	1322	T9	3.5	38.4446	–109.7047	12 (14)	3.11 ± 0.19	IRSL	2.9 ± 0.5 (n = 7)	973.9 ± 111.2	312.8 ± 23.0
Reach D											
USU-3733	1198	T3	1.6	38.4305	–109.7407	13 (15)	3.52 ± 0.21	IRSL	2.9 ± 0.3 (n = 6)	263.6 ± 22.1	74.8 ± 5.8
USU-3609	1223	T5	2.0	38.3591	–109.7389	10 (13)	3.00 ± 0.18	IRSL	2.6 ± 0.3 (n = 5)	595.6 ± 116.9	198.9 ± 19.7
Gypsum											
USU-3051	1195	T3	10	37.9971	–110.050	19 (27)	1.90 ± 0.05	OSL	–	98.5 ± 5.3	51.8 ± 3.0

(B) TCN Surface Exposure Age Information

Sample	Elevation (m)	Deposit	Depth (m)	Location (NAD 83) Lat (°N)	Long (°W)	Surface elevation (m)	Age (ka)
JRNC-profile	1298	T8	0.25–2	38.4958	–109.6535	1300	265 ± 34††

*Samples are listed by reach, in stratigraphic order from T2 to T10. Annotation 'a,b,c,d' represents the consecutively younger deposits in the T4 suite.
†Number of aliquots used in the age calculation and number of aliquots analyzed (in parentheses).
§Data relevant to dose rate calculation is included in the Supplemental Material (see text footnote 1); Gy—Grays.
#See the Supplemental Material for details on different luminescence methods used and the fading correction for infrared stimulated luminescence (IRSL) measurements; pIR^{250}—post IR at 250 °C ; OSL—optically stimulated luminescence.
**Equivalent dose (D_E) calculated using a weighted mean.
††Age error reported is within 95% uncertainty.

level changes and bedrock controls such as salt tectonics drive landscape evolution that continues long after orogenic tectonics has ceased.

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