GEOSCIENCES
COLORADO STATE UNIVERSITY

Warner College of Natural Resources
Department of Geosciences
322 Michael Smith Natural Resources
Fort Collins, Colorado 80523-1482

December 31, 2024

Final Report on Discovery Pool-funded research
Tracking the timing and dynamics of Colorado River canyon incision through study of river terraces near Dewey, UT

Dear Sam and others,

Enclosed is the Final Report of findings for our January 2023 CNHA Discovery Pool grant for geochronological study of terraces along the Dewey reach of the Colorado River. This work was conducted with the support of the BLM Moab Field Office, who reviewed our field plan in April 2023 and determined that our work did not require BLM authorization or specific permitting. The enclosed report is also being sent to Dave Pals in that office for their review.

I am thankful for the Discovery Pool grant! It was approved two years ago. All field and lab-prep work was completed by the end of summer 2023. For the past one and a half years, we have been waiting for luminescence-instrument results to incrementally arrive, as instrument time at the USU Luminescence Lab is always backlogged and in high demand. Indeed, the latest sample results just arrived, and therefore, albeit late, I am reaching the goal of delivering this Final Report at the end of this calendar year. Here we are.

The results of this Discovery Pool research are likely to appear as part of a larger dataset in a scientific-journal publication in the upcoming years. When it does, the CNHA Discovery Pool will be prominently acknowledged!

Sincerely,

Joel L. Pederson
Professor and Head

FINAL REPORT

Tracking the timing and dynamics of Colorado River canyon incision through study of river terraces near Dewey, UT

December 31, 2024

Joel Pederson - Geosciences, Colorado State University

Michaela Shallue and Natalie Tanski - Utah State University graduate students

Federal agency partner: BLM Moab Field Office

Introduction

The timing and causes of river incision across the Canyonlands district and the greater Colorado Plateau have been the subjects of speculation since the dawn of modern geology in the late nineteenth century. As techniques in the numerical dating of geological features have emerged over the past few decades, it has allowed new research questions about regional landscape evolution to be addressed more concretely. For example, geoscientists have confirmed that Grand Canyon was largely cut in the Pliocene (5.3 to 2.6 million years ago), driven mostly by the integration of the Colorado River off the high plateau and into the low Basin and Range (Lucchitta, 1972; Karlstrom et al., 2014). It is well established by theory and models that after a fall in baselevel such as this, incision along rivers propagates upstream as a wave over geologic time while diffusing or declining in amplitude along the way.

Recent documentation and numerical dating of Colorado River terraces, which are abandoned channel deposits and landforms marking river position in the past, have provided evidence for this transient incision in Canyonlands (Tanski et al, 2023). A pulse of ~200 meters of incision has propagated upstream over middle-late Pleistocene time, specifically the past ~300 thousand years, through upper Glen Canyon, Cataract, Meander Canyon, and then hypothetically past Moab, through Professor Valley, to Westwater Canyon (Fig. 1).

In this study, we have developed a dataset from Colorado River terraces in the reach around and above Dewey, on BLM-managed land. This study area lies upstream of most prior research on the river, and our hypothesis is that the wave of incision should have arrived more recently at Dewey (<250 thousand years ago) than downstream and that late Pleistocene incision rates should therefore be faster than downstream. Through surveying relict Colorado River terraces and sampling and dating them by the latest luminescence techniques, we are able to track the history of river incision and canyon cutting, providing evidence of transient incision and an estimate of its celerity (upstream velocity of the wave). This more complete picture of the recent canyon-cutting history of the region provides a fascinating story for interpretating the dynamic landscape evolution of Canyonlands for the public.

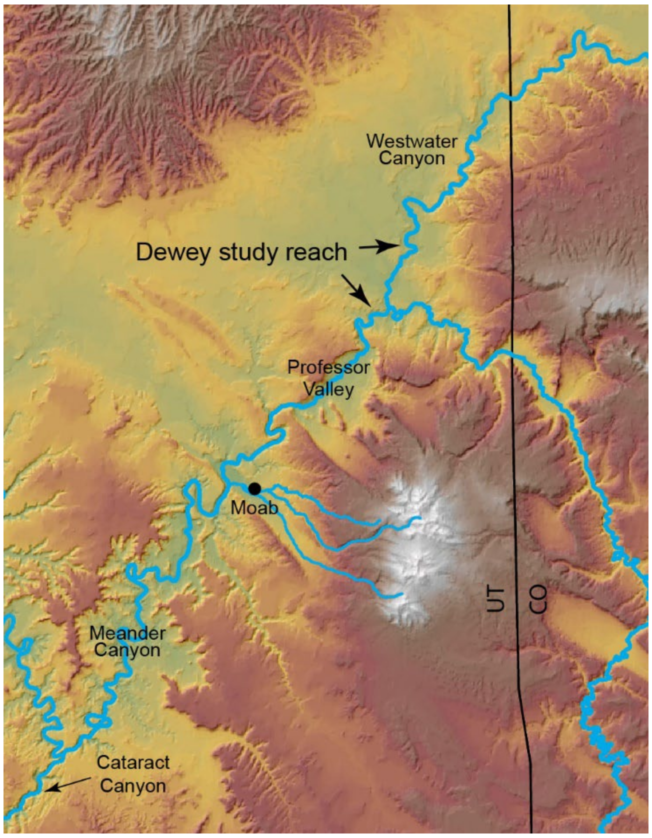


Figure 1. Regional map showing Dewey study area and canyon reaches upstream and downstream along the Colorado River.

Background

Trunk channels such as the Colorado River are the arteries that carry signals through landscapes; they set the level to which tributaries and hillslopes deliver water and sediment. John Wesley Powell, after experiencing canyon country, was the first to highlight the idea that drainages seek this "baselevel", driving the erosion of landscapes. Observations as well as lab experiments and computational models tell us that as baselevel falls – for example, by river capture, sea-level fall, or relative uplift of terrain – incision proceeds from downstream to upstream, sometimes expressed as a steepness anomaly (knickpoint) or waterfall that recesses over time. Knickpoints on larger rivers that flow through relatively weak rock, like the Colorado through the Plateau, are more subtle features that diffuse over entire reaches. Yet, even where knickpoints are not evident, large-scale patterns of incision are recorded by remnant river-terrace deposits in the landscape, and the history of erosion can be reconstructed if the terraces can be numerically dated.

Over the past several years, three research projects by the PI and students in the Canyonlands region have revealed how variable and dynamic river incision has been over the Pleistocene epoch. Exhaustive study of Colorado River terraces downstream, from upper Glen Canyon up through Cataract and Meander canyons reveals evidence for at least one wave of rapid incision that has propagated through those canyons starting at ~300 thousand years ago, forming the inner ~200 m of canyon depth (Tanski et al., in press). The most recent wave of river incision in Meander Canyon has waned, declining in rate, over the past 60,000 years (Tanski et al., 2023).

Upstream, a graduate Thesis by James Mauch (2018) on the geomorphology of Pack and Mill Creeks, which flow through Moab Valley to the Colorado, revealed that tributary incision rates were near zero for an extended period of Pleistocene time until ~250 thousand years ago. At that time, incision increased rapidly, driving canyon cutting as well as the subsidence of Spanish-Moab Valley as the landscape responded to the suddenly dropping baselevel of the Colorado River.

Farther upstream in the area of focus here, a published study (Jochems and Pederson, 2015) reconstructed recent Colorado River history from the mouth of Castle Creek up through Professor Valley to Dewey. They document deformation terraces by salt tectonics, as well as evidence that incision rates increase in the upstream direction -- from 0.6 mm/yr near Castle Creek to perhaps 0.9 mm/yr at Dewey. This previous work provided only optically-stimulated luminescence (OSL) ages that were unexpectedly young around Dewey, and for only the lowest terraces in the landscape. Nevertheless, this tentative result inspired the hypothesis that a recent wave of incision has propagated upstream past these locations and is currently expressed, in part, as the steep reach of Westwater Canyon (Fig. 2).

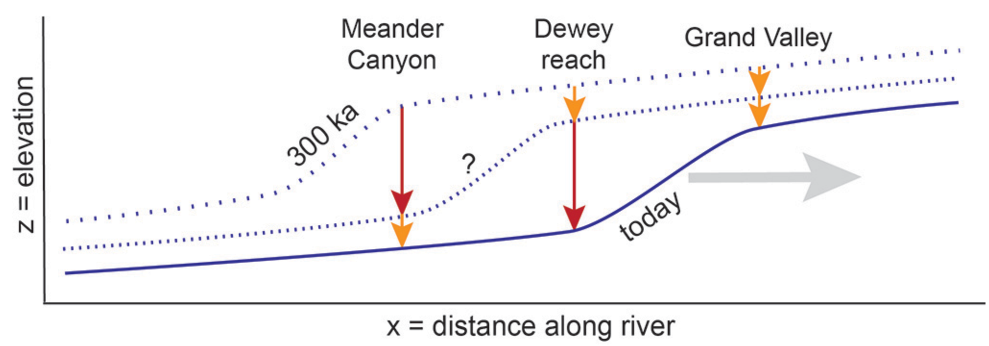


Figure 2. Schematic of transient incision along an evolving river profile, with a steeper reach of rapid incision migrating upstream through time, hypothetically consistent with regional datasets. Downstream in Meander Canyon, incision waves have driven rapid incision starting ~300 thousand years ago until apparently slowing in the late Pleistocene. Upstream through Professor Valley and Dewey, there has been somewhat more recent, rapid incision, as documented in this study. Work on terraces in Grand Valley upstream of Westwater indicates somewhat slower incision over late Pleistocene time (Aslan et al., 2019).

Although this previous work is consistent with the hypothesis depicted in Fig. 2, data from higher and older terraces are needed in the Dewey reach and re-dating of the suspiciously young lower terraces is necessary to definitively test and measure the amplitude and celerity of any incision wave.

Methodology

Reconnaissance for sandy terrace deposits and GPS surveying and sampling of those sand lenses occurred in March, 2022 and April, 2023. River terraces in the Dewey reach were already located and mapped by Doelling (1996), but their exact numbering and stratigraphic position in the landscape was modified upon our closer inspection. Terrace deposits in any given reach are designated by numbers starting with terrace 1 (T1) representing the entire Holocene floodplain along the valley bottom. Then, incrementally increasing numbers are designated for gravel remnants proceeding higher in the landscape and back through geologic time. Sampling of sand lenses for luminescence dating was accomplished by driving 1.5-inch diameter steel tubes into small excavations along the flanks of terrace landforms, and both ends of the tube are sealed for transport to the darkroom lab (Fig. 3). Additional, small-volume samples of the immediately surrounding sediment were collected for dose-rate chemistry and moisture content.

Figure 3. Above – photograph facing NE overlooking the Colorado River valley immediately upstream of Dewey Bridge. The slope on the side of the T6 terrace deposit is locally excavated where sandy beds were discovered for luminescence sampling. Left – excavations proceed to a minimum depth below any local deposits transported along the modern slope, revealing in situ *Colorado River sediment with original structures for documentation and sampling. All excavations were filled by repatriation of the extracted sediment.*

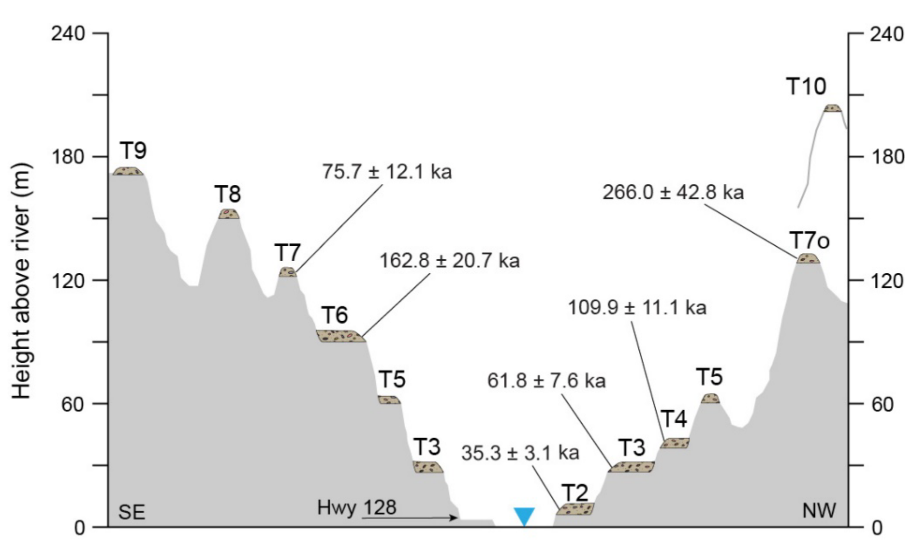
Sample processing at the USU Luminescence Lab was completed following standard procedures over the summer and fall of 2023 by student-PI Michaela Shallue, under the training and supervision of Lab Manager Dr. Michael Strange.

Luminescence dating is a family of techniques that utilize how quartz and feldspar mineral grains behave as dosimeters in earth materials. That is, as these minerals are subject to radiation in their immediate surroundings, they accrue molecular-scale damage in the form of electrostatic charge (trapped electrons). This charge accumulates as a function of local dose rate and the length of time in burial, shielded from solar radiation that would stimulate and release the trapped charge. Exposure of the sediment to targeted energy in the form of heat or light in the laboratory stimulates the escape of electrons in controlled fashion. This imparts a luminescence signal that is proportional to the amount of dose the grains endured over time. This measured luminescence signal, along with knowledge of the grain's trapping properties and the environmental dose rate, allows us to calculate the duration of geologic time the grains were buried in the deposit – providing a depositional age. Optically-stimulated luminescence on quartz is a very common method of geochronology, but it is only applicable to materials less than ~150,000 years old due to the limited amount of charge that quartz can retain. Infra-red-stimulated luminescence (IRSL) dating of feldspar takes advantage of that mineral's greater capacity for trapped charge, enabling the dating of deposits approaching half a million years in age. IRSL dating includes an additional adjustment for the rate the trapped charge leaks or fades with time, involving direct instrumental measurement of this fading behavior of the sampled grains. Both OSL and IRSL analyses were conducted in this research.

Results

Ten terrace levels are evident in the landscape along the Colorado River in the Dewey Reach, spanning up to 205 m in height above the modern river level (Fig. 4). The highest T10 and T9 deposits cap mesas on the shoulders of the broad canyon. No sandy lenses were evident for sampling in those poorly exposed, highest terraces. Similarly, the next-highest T8 gravel, at 152 m height, was not able to be dated. Although a sample was collected, it was not processed because we deemed that it was likely from weathered sandstone bedrock just beneath the gravel rather than Colorado River sand within the gravel.

Figure 4. Cross-sectional diagram of Colorado River terrace deposits found in the Dewey Reach. Schematic view is looking downstream and vertically exaggerated, with terraces plotted at their surveyed height relative to the modern river surface. Luminescence age results are labeled.



Most of the other, lower terrace levels were sampled. A terrace level deemed the T7o (“o” for older) was sampled ~3 km downstream (SW) from Fish Ford in the upstream part of the study reach, providing our oldest age result. T2, T3, and T4 were redated with samples from new exposures to compare to the earlier results from the same lower terraces in Jochems and Pederson (2015). No sample was obtained from T5 because no sandy intervals were evident in the field. In all, six samples were processed and dated. Table 1 includes the field-sample number, the USU lab sample number, terrace position, sample location, absolute elevation, and the depth of the sampled sand lens below the terrace-landform top.

Table 1. Dewey reach luminescence samples.

sample	USU #	terrace	Northing (UTM)	Easting (UTM)	elevation (m)	depth (m)
Cat_NT_29	USU-4155	T7 south of bridge ~124 m	4296530.5	646984.2	1371.1	3.0
Cat_NT_30	USU-4156	T6 south of bridge ~92 m	4296860.6	647166.4	1335.9	2.5
Cat_NT_31	USU-4157	T4 south of bridge	4296747.8	646574.9	1289.5	3.0
Cat_NT_32	USU-4158	T3 north of bridge	4297633.0	647223.0	1277.0	1.0
Cat_NT_36	USU-4340	T7o Fish Ford ~130 m	4305840.3	650407.7	1383.6	3.5
Cat_NT_37	USU-4341	T2 Fish Ford, strath = 10 m	4311469.5	653306.5	1272.7	2.5

Luminescence age results from these six samples range from about 35 thousand years old (ka) for T2 up to about 265 ka for the T7o. Table 2 identifies which technique was used, the number of aliquots (sub-samples, or disks) with robust results that are included in the age calculation as well as the total number of aliquots run for each sample (in parentheses). The local environmental dose rate is calculated from the concentration of radioactive elements in the surrounding sediment plus cosmogenic dosing based upon the burial depth and latitude, reduced by a moisture-content (estimated as 5% for all samples) factor. The De is the measured equivalent dose (the stored luminescence signal) from each sample in greys, with 2-sigma error reported. For IRSL samples, this is adjusted up to account for the measured fading rate of the sample. The final age is determined by dividing the De by the total dose rate, and reported here with very conservative, 2-sigma errors.

Table 2. Dewey reach luminescence sample geochronology results.

USU #	tech.	#disks	dose rate (Gy/ka)			De (Gy, 2se)			fading (%/decade)	*age in ka (2se)*		
USU-4155	IRSL	11(15)	3.68	±	0.17	278.3	±	70.5	IR50: 2.95 ± 0.2	*75.7*	*±*	*12.1*
USU-4156	IRSL	7(13)	3.30	±	0.16	537.9	±	86.7	IR50: 2.59 ± 0.07	*162.8*	*±*	*20.7*
USU-4157	OSL	17(21)	2.30	±	0.09	252.3	±	31.4		*109.9*	*±*	*11.1*
USU-4158	OSL	13(21)	2.93	±	0.11	181.0	±	33.7		*61.8*	*±*	*7.6*
USU-4340	IRSL	6(13)	4.11	±	0.20	1093.2	±	278.3	IR50: 3.91 ± 0.46	*266.0*	*±*	*42.8*
USU-4341	OSL	16(21)	3.35	±	0.13	118.1	±	8.4		*35.3*	*±*	*3.1*

One of these age results is clearly erroneous – from sample USU-4155 taken from T7. Although the luminescence data are robust analytically, the age of deposition that is impossibly recent/young, given the high landscape position of the T7. Stratigraphically, the true depositional age of the T7 must have been at a time between when the higher T7o was deposited and the lower T6 was deposited. Instead, the resultant age is at least 100 thousand years too young. Based upon the location of the terrace and the down-wind sample position, it is hypothesized that this result actually represents the timing of eolian sand being deposited or reworked along the flank of the T7 terrace remnant. This erroneous age is not included in the analysis below.

Discussion of Colorado River incision history

A plot of each terrace-deposit's central age versus its height above the modern river illustrates the trend of the river lowering (incising) through the bedrock of the canyon or valley through time (Fig. 5). The simplest rate calculation is a least-squares-average trendline fit through the five robust datapoints of the plot. The slope of this line provides the linear incision rate over the timespan of the results: 0.54 meters/thousand years, or 540 meters/million years (m/my). This rate is indeed very fast for the Colorado Plateau. For example, the overall average incision rate from Meander Canyon downstream is 0.4 m/my (Tanski et al., 2023).

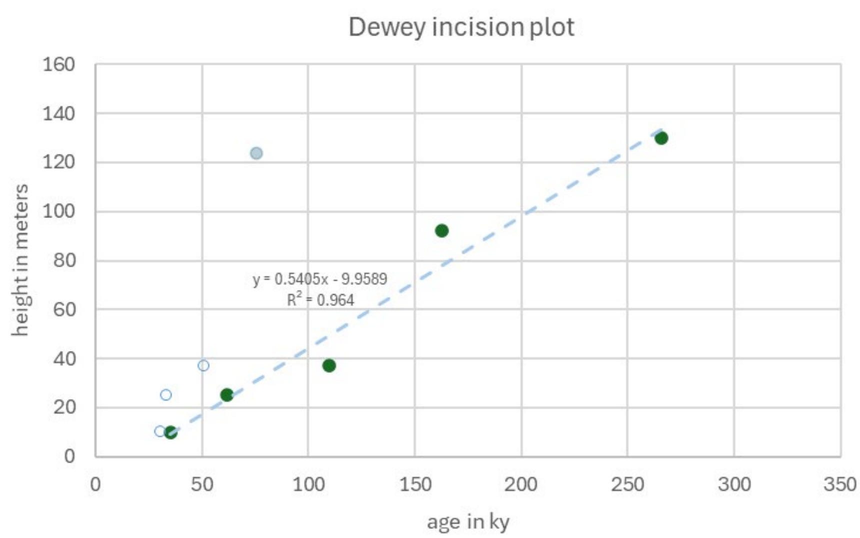


Figure 5. Plot of terrace age versus elevation, with least-squares trendline fit through the five solid-green datapoints. Equation of this trendline is reported, with the slope representing the incision rate over that timespan (540 m/my), and the y-intercept being the depth the line projects to below the modern river surface (-10 m). Faded gray datapoint is the erroneously young result from the T7. Open circles are age results from the T2, T3, and T4 reported in Jochems and Pederson (2015).

New results confirm the T3 and T4 ages at Dewey reported in Jochems and Pederson (2015) are inaccurate and too young, safely assuming the sampling procedures and lab analyses are improved in this study. Additional evidence that these new age results are correct, is that they match the ages of the same-numbered trunk-river terraces in several other regional studies – downstream in Meander Canyon and Grand Canyon, upstream in Grand Valley, and at Crystal Geyser, 75 km to the west on the Green River. T3 is 75-60 ka in all of these study reaches and clearly coincides with the glacial epoch of marine-isotope stage 4, whereas the main T4 deposit is 110-90 ka everywhere in the Colorado Plateau.

Despite the robust fit of the trendline in Figure 5, the published record downstream in the Meander Canyon reach indicates that Colorado River incision is probably not linear or constant over 100-ky timescales. In Figure 6, orange datapoints display Meander Canyon terrace central ages and heights from Tanski et al. (2023), for comparison to the green-blue Dewey dataset.

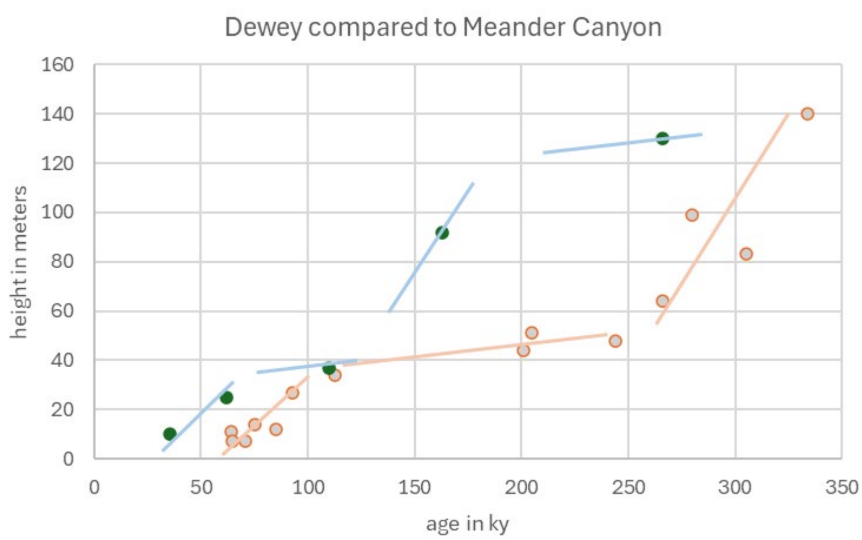


Figure 6. Incision-history diagram, comparing this study's results from the Dewey reach to published results from Meander Canyon, 50-100 km downstream (Tanski et al., 2023).

The orange trendlines in Figure 6 illustrate the unsteady history of incision through time evident in Meander Canyon, with alternating rapid and slow episodes, each spanning many 10s of thousands of years. In comparison, the five Dewey datapoints are, admittedly, insufficient in number to resolve such distinct episodes. For future work, the missing ages of T5 and T7 are necessary to resolve whether incision is unsteady or not, and the highest/oldest undated terraces should be a focus of future research as well.

Yet, the blue trend lines added to Figure 6 illustrate that a similar set of rate changes through time are certainly possible in the Dewey reach. In particular, over the past 120 ky of record provided by the three datapoints of T4 – T2, it is likely that an episode of rapid incision started ~70 ka, preceded by more moderate incision rates around T4 time. Taking this supposition to a next-level, the wave celerity of transient incision can be estimated. The offset in age of the youngest terraces in the two reaches (the difference in x-axis age between the youngest, steep orange and steep blue lines in Figure 6) is ~35 ky, suggesting it took 35 ky for a pulse of incision to propagate from Meander Canyon to Dewey. Taking an average distance between Meander and Dewey of ~70 km, for convenience, the estimated celerity is ~2 km per thousand years, or 2 m/yr. Tanski et al. (in press) estimate that incision-wave celerities across the central Colorado Plateau range from 0.1 to 2 m/yr, with 1 m/yr measured within Meander Canyon where the bedrock is the same highly erodible, Mesozoic and Permian lithologies found all along the stretch between the Meander and Dewey reaches.

The transient-incision hypothesis being tested in this study had two-parts -- that a pulse of river incision has reached Dewey more recently than the 250 ka recorded by Mauch downstream at Moab, and that incision rates at Dewey since that time are faster than measured downstream. The new dataset of this study is consistent with both of these predictions, providing more concrete support that a wave of incision has propagated through these canyons. In fact, to my knowledge, the results of this study add to the best example on our planet of transient incision being captured and measured at a large scale through a river-terrace record.

References Cited

Aslan, A., Karlstrom, K.E., Kirby, E., Heizler, M.T., Granger, D.E., Feathers, J.K., Hanson, P.R., and Mahan, S.A., 2019, Resolving time-space histories of Late Cenozoic bedrock incision along the Upper Colorado River, USA: *Geomorphology*, v. 347, p. 106855, doi:10.1016/J.GEOMORPH.2019.106855.

Doelling, H.H., 1996, Geologic map of the Dewey quadrangle, Grand County, Utah: Utah Geological Survey Map 169, scale 1:24 000, 2 sheets, 21 p. text.

Jochems, A.P., and Pederson, J.L., 2015, Active salt deformation and rapid, transient incision along the Colorado River near Moab, Utah: *Journal of Geophysical Research: Earth Surface*, v. 120, p. 730–744, doi:10.1002/2014JF003169.

Karlstrom, K., Lee, J., Kelley, S. *et al.* Formation of the Grand Canyon 5 to 6 million years ago through integration of older palaeocanyons. *Nature Geoscience* **7**, 239–244 (2014). https://doi.org/10.1038/ngeo2065

Lucchitta, I., 1972, Early history of the Colorado River in the Basin and Range province: *Bulletin of the Geological Society of America*, v. 83, p. 1933–1948, doi:10.1130/0016-7606.

Mauch, J., 2018, Quaternary Incision, Salt Tectonism, and Landscape Evolution of Moab-Spanish Valley, Utah: MS Thesis, Department of Geology, Utah State University, 235 pp., doi:10.1192/bjp.112.483.211-a.

Tanski, N.M., Pederson, J.L., Rittenour, T.M., and Hidy, A.J., 2023, Pleistocene Colorado River terraces in the canyonlands region (Utah, USA) record unsteady, transient incision and growth of the Cataract Canyon knickzone by salt tectonics: *Geology*, v. 52, p. 99–104, doi:10.1130/G51599.1.

Tanksi, N., Pederson, J., Hidy, A., Rittenour, T., and Mauch, J., *in press*, The mystery of baselevel controls in the incision history of the central Colorado Plateau: *AGU Advances*, 2024AV001359