

Rapid river incision across an inactive fault—Implications for patterns of erosion and deformation in the central Colorado Plateau

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ABSTRACT

The Colorado Plateau presents a contrast between deep and seemingly recent erosion and apparently only mild late Cenozoic tectonic activity. Researchers have recently proposed multiple sources of epeirogenic uplift and intriguing patterns of differential incision, yet little or no quantitative constraints exist in the heart of the plateau to test these ideas. Here, we use both optically stimulated luminescence (OSL) and uranium-series dating to delimit the record of fluvial strath terraces at Crystal Geyser in southeastern Utah, where the Little Grand Wash fault crosses the Green River in the broad Mancos Shale badlands of the central plateau. Results indicate there has been no deformation of terraces or surface rupture of the fault in the past 100 k.y. The Green River, on the other hand, has incised at a relatively rapid pace of 45 cm/k.y. (450 m/m.y.) over that same time, following a regional pattern of focused incision in the “bull’s-eye” of the central plateau. The Little Grand Wash fault may have initiated during Early Tertiary Laramide tectonism, but it contrasts with related structures of the ancestral Paradox Basin that are presently active due to salt dissolution and focused differential erosion. We also hypothesize there may be a Pliocene component of fault slip in the region linked to broad-wavelength erosional unloading, domal rebound, and extension. An apparent rapid decrease in incision rates just upstream through Desolation Canyon suggests the Green River here may have recently experienced an upstream-migrating wave of incision.

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INTRODUCTION

The Colorado Plateau of the western United States is famous for the spectacular erosional exhumation of a stratigraphic record that has been subject to only mild tectonic deformation over Phanerozoic time. Overall erosion of the region is linked to a pulse of late Cenozoic incision driven by the integration and base-level drop of the Colorado River off the southwestern margin of the plateau to the Gulf of California (Lucchitta, 1972; Pederson et al., 2002). That plateau margin in the western Grand Canyon area is the focus of scientific controversy because of its complex and long paleocanyon-cutting history spanning the Cenozoic (cf. Polyak et al., 2008; Karlstrom et al., 2008; Wernicke, 2011; Flowers and Farley, 2012). However, the southwest margin contrasts with the core of the Colorado Plateau physiographic province, including our study area, which has a notably younger and more active record of erosion and landscape evolution (Hoffman et al., 2011; Pederson et al., 2013).

Several sources of middle-late Cenozoic regional uplift have been recently proposed for the Colorado Plateau. These include buoyancy modifications of the mantle lithosphere linked to an ancestry involving the Farallon slab (e.g., Humphreys et al., 2003; Roy et al., 2009), regionalized dynamic support from convecting asthenosphere and potential mantle drips (Moucha et al., 2009; van Wijk et al., 2010; Levander et al., 2011), and isostatic rebound due to unloading by erosion and extension (Pederson et al., 2002; Roy et al., 2009; Karlstrom et al., 2012). Indeed, the flexural feedback between late Cenozoic exhumation and rock uplift is focused upon the central plateau, where more than 3 km of section have been removed in areas (Nuccio and Condon, 1996; Pederson et al., 2002; Hoffman et al., 2011; Karlstrom et al., 2012). The patterns of incision and their relation to these distinct potential sources of regional uplift and other controls are also highly debated (e.g., Karlstrom et al., 2012; Pederson and Tressler, 2012; Darling et al., 2012; Pederson et al., 2013), but there are few well-constrained geomorphic records available in the heart of the Colorado Plateau to address these problems.

An exception to the general lack of deformation in the Colorado Plateau is the episodic salt tectonics in the central plateau linked to unloading of Pennsylvanian evaporite deposits of the

ancestral Paradox Basin. In the cases of the Grabens district of Canyonlands National Park in southeastern Utah and the Onion Creek diapir to the north, it has been established that deformation is ongoing today (e.g., Colman, 1983; Huntoon, 1988; Furuya et al., 2007). It also has been widely speculated that localized dip-slip faulting and E-W-oriented graben formation continued into the Quaternary or is still active in the central plateau (Colman and Hawkins, 1985; Doelling et al., 1988; Shipton et al., 2004). The Little Grand Wash and Salt Wash (aka Ten-Mile) Graben faults crossing the Green River are examples that have been a focus of recent work (Fig. 1A). These faults have acted as pathways for fluid flow, resulting in a set of abandoned and modern spring-travertine mounds focused along the fault traces (Shipton et al., 2004; Dockrill and Shipton, 2010; Kampman et al., 2012). The travertine mounds themselves have been incised, permitting detailed study of their internal chronostratigraphy (Burnside et al., 2013), which may constrain Quaternary movement on these structures. Yet, no solid geomorphic constraints on the timing and rates of faulting have been reported for the region.

River terraces are valuable markers for these tectonic geomorphology problems, enabling us to quantify rates of erosion, faulting, and land-

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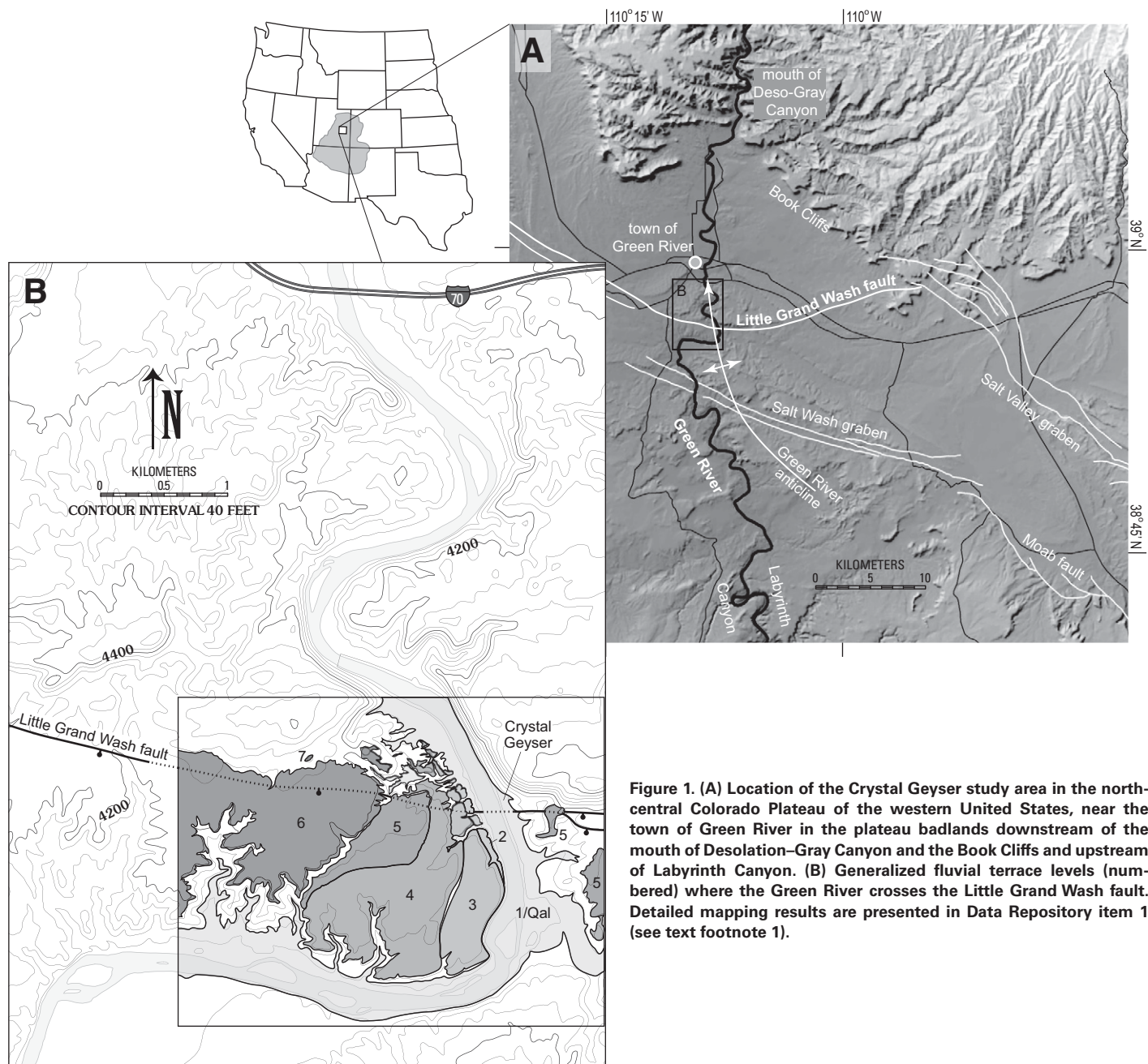


Figure 1. (A) Location of the Crystal Geyser study area in the north-central Colorado Plateau of the western United States, near the town of Green River in the plateau badlands downstream of the mouth of Desolation-Gray Canyon and the Book Cliffs and upstream of Labyrinth Canyon. (B) Generalized fluvial terrace levels (numbered) where the Green River crosses the Little Grand Wash fault. Detailed mapping results are presented in Data Repository item 1 (see text footnote 1).

landscape evolution. The trunk drainages of the plateau have locally preserved a sequence of gravelly strath (thin sediment cover) and thick fill terraces that record both incision and responses to climate change (e.g., Marchetti and Cerling, 2005; Pederson et al., 2006). Through stratigraphic and geochronologic study, these can be used to constrain rates of local faulting and also provide time-integrated rates of incision along the trunk drainages that set the pace for broader erosion in the landscape.

The goal of this study is to document any late Quaternary faulting and the rate of river

incision at a location in the north-central Colorado Plateau where such constraints are missing. We utilize the archive of Green River terrace deposits and associated travertine near Crystal Geyser, at the intersection of the Green River and the Little Grand Wash fault (Fig. 1B; DR1 map¹). Field and geochronology results at Crystal Geyser reveal clear evidence for active river incision, but not active faulting, helping illumi-

nate the patterns of erosion and deformation in this landscape.

BACKGROUND

Setting

The Crystal Geyser study area lies along the Green River, 7 km south of the town of Green

¹GSA Data Repository Item 2013319, a 1:12,000 scale surficial geologic map of the study area (item 1) and tables, graphs, and descriptions of luminescence methods and results (item 2), is available at www.geosociety.org/pubs/ft2013.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

River, Utah (Fig. 1A). Flowing to the south, the river exits Desolation–Gray Canyon through the Book Cliffs upstream and crosses low-relief, arid badlands underlain by the upper Cretaceous Mancos Shale before entering Labyrinth Canyon downstream of the study area. As the river approaches the Little Grand Wash normal fault, the lower Cretaceous Cedar Mountain and the Jurassic Morrison and Summerville Formations rise in the footwall, forming a shallow and short canyon. Where the river crosses into the hanging wall, the Mancos Shale is brought to river level again, the valley broadens, and there is preserved a suite of seven gravelly strath terraces in an interior bend of the river (DR1 map [see footnote 1]).

Faulting and Travertine

The S-dipping Little Grand Wash normal fault has an arcuate surface trace of 61 km and a total vertical separation in the study area of 180–210 m (Fig. 1A; Dockrill and Shipton, 2010). Like the other NW–SE-oriented normal faults of the region, the Little Grand Wash fault is presumed to sole in the Paradox Formation evaporites at depth, though a deeper link to basement structures is also possible (Black and Hecker, 1999; Trudgill, 2011). Previous regional mapping documented river terraces overlying and obscuring the trace of the fault (Doelling, 2002), implying little or no slip over an undetermined amount of Quaternary time. Indeed, the Little Grand Wash fault is not included in the U.S. Geological Survey and Utah Geological Survey’s listing of active Quaternary faults (Black and Hecker, 1999). On the other hand, several neighboring and analogous faults such as the Salt Wash Graben faults immediately to the south and the associated Salt Valley Graben and Moab faults to the east and southeast are considered active (Fig. 1A; Hecker, 1993). Finally, based upon initial mapping of traver-

tine and fault relations, previous workers have proposed some amount of late Pleistocene fault movement on the Little Grand Wash fault (Williams, 2004; Shipton et al., 2004).

Crystal Geyser itself is a periodic, CO₂-charged geyser created by an oil exploration well drilled in A.D. 1935 (McKnight 1940). Travertine precipitates out of the CO₂-saturated water exiting the well, and there is a 113-k.y.-long record of fracture-fill and travertine formation along the central part of the fault trace (Burnside, 2010; Burnside et al., 2013). Previous work at the site has generally focused on the Little Grand Wash fault and Salt Wash Graben as a conduit for CO₂ and water, and the travertine record we utilize here for uranium-series dating has been interpreted to record pulses of CO₂ leakage linked to climate changes (Kampman et al., 2012).

Typical travertine along the Little Grand Wash fault consists of centimeter-thick to tens-of-centimeters-thick, subhorizontal veins of radiating acicular calcite and aragonite crystals that have botryoidal or mammillated top surfaces. The A.D. 1867 Powell expedition documented “satin spar” at this location (Powell, 1875), which may be these ray-crystal calcite veins. These veins have been interpreted to generally form under saturated conditions, though occasionally they contain stalactite-like structures suggesting dissolution and reprecipitation of calcite within open cavities above the water table (Dockrill, 2006; Gratier et al., 2012). Ancient travertine deposits along the fault are found up to 37 m above those presently forming at Crystal Geyser, and they tend to form resistant caps to erosional remnants. An important factor for this study is a key travertine body just east of the Green River that issues from one such remnant mound, and which has been dated using uranium-series dating. This travertine stratigraphically underlies and interfingers with tributary/piedmont alluvium in a complex terrace remnant graded to a

past level of the main-stem Green River (DR1 map [see footnote 1]; P6/5 on cross section in Fig. 2; Table 1).

METHODS

Surficial deposits and terraces along the main-stem Green River corridor in the area of Crystal Geyser have been mapped at a scale of 1:12,000 (DR1 map [see footnote 1]). The heights of terrace treads (top surfaces) and straths (basal unconformities) were recorded in survey transects normal to the river channel using a real-time kinematic global positioning system (GPS) system. Both main-stem and local piedmont deposits were sampled and dated by optically stimulated luminescence (OSL) and uranium-series dating. OSL samples date the timing of sediment deposition and burial during the episode of base-level stability and lateral planation marked by the given strath terrace. The uranium-series results reported here are a small subset of those reported in Burnside (2010), specifically, travertine samples that underlie and interfinger with piedmont-terrace alluvium or that relate to Holocene floodplain deposits adjacent to Crystal Geyser. These samples are not of secondary cement, and results are interpreted as ages of crystallization for the travertine and therefore help constrain the age of the interfingering and overlying fluvial gravels (Table 1).

Rare lenses of fine- to coarse-grained, cross-bedded, fluvial sand interbedded within otherwise cobbly terrace deposits were targeted for OSL dating. Samples were collected in aluminum tubes, with depth, elevation, and latitude/longitude noted for calculation of cosmic contribution to dose rate. Representative samples for the determination of water content and radiometric dose rate were collected, with sediment for dose rate sampled within the relatively homogeneous sand lenses and taken systematically within 20 cm surrounding the OSL sam-

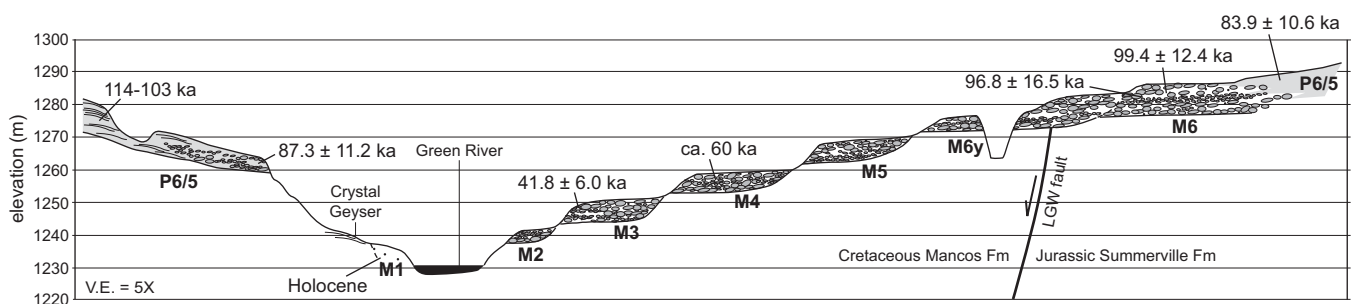


Figure 2. Cross-sectional profile of the terrace stratigraphy at Crystal Geyser, looking downstream, with age results from optically stimulated luminescence (OSL) and uranium-series dating (Table 1). Y-axis is surveyed elevation of terrace treads and basal straths above the modern base-flow stage of the Green River, whereas the relative width of deposits is schematic, representing their lateral extent in the landscape. M—main-stem Green River strath terraces, P—deposits of local piedmont systems graded to main-stem terraces. The M6y deposit’s undeformed and capping relation to the Little Grand Wash (LGW) fault is shown in Figure 3. V.E.—vertical exaggeration.

TABLE 1. CRYSTAL GEYSER GEOCHRONOLOGY SUMMARY

OSL sample	Deposit*	Depth (m)	No. aliquots	Equivalent dose (Gy) (overdispersion)	Dose rate (Gy/k.y.)	OSL age (ka) [†]
USU-271	M3	3.0	27 (35)	118.03 ± 12.12 (20.1%)	2.83 ± 0.16	41.8 ± 6.0
USU-278	M4	1.7	27 (43)	145.72 ± 15.31 (23.4%)	2.47 [§]	~60 [§]
USU-256	P6/5	4.0	34 (45)	187.39 ± 15.03 (19.4%)	2.15 ± 0.12	87.3 ± 11.2
USU-279	P6/5	2.5	25 (45)	222.81 ± 17.45 (16.4%)	2.66 ± 0.14	83.9 ± 10.6
USU-780	M6	2.5	24 (48)	232.27 ± 32.20 (28.1%)	2.40 ± 0.13	96.8 ± 16.5
USU-781	M6	1.9	27 (41)	227.79 ± 17.27 (14.9%)	2.29 ± 0.12	99.4 ± 12.4
U-series sample	Deposit	Total U (ppm)		Total Th (ppb)	²³⁰ Th/ ²³² Th	Age (ka) [‡]
LG.03.42AZ	P6/5	4.754		—	—	103.2 ± 1.5
LG.03.42AX	P6/5	5.093		0.38	888,662	106.5 ± 0.5
LG.03.42AF	P6/5	4.220		0.06	675,748	109.6 ± 0.9
LG.03.42AD	P6/5	5.076		0.04	905,311	113.9 ± 0.6

Note: OSL—optically stimulated luminescence.

*Organized by stratigraphic position; M—main-stem Green River, P—local piedmont drainages graded to main stem.

[†]Reported ages are at 2σ with random and systematic errors combined in quadrature.

[§]Mean dose rate of other samples used due to erroneously high chemistry results (see text and Table DR2 [see text footnote 1]); age is only an estimate.

[‡]U-series ages are at 2σ, with systematic analytical error and error on decay constants propagated into age-error calculation.

ples. For radiogenic dose rate, the bulk sediment concentrations of K, Rb, U, and Th were measured using inductively coupled plasma–atomic emission spectrometry (ICP–AES) and ICP mass spectrometry (MS) techniques. Total dose rates were calculated using the methods of Aitken (1998) and Prescott and Hutton (1994). OSL measurements were conducted at the Utah State University Luminescence Laboratory on a quartz fraction ranging within 75–250 μm using a RISO TL/OSL-DA-20 reader, following the single-aliquot regenerative (SAR) protocol of Murray and Wintle (2000). Thirty-five to 48 aliquots were measured from each sample, with optical ages calculated using the central-age model of Galbraith et al. (1999) on those aliquots that passed standard criteria for quality and optical behavior. Detailed OSL laboratory methods, including such analytical criteria, and full equivalent-dose distribution and dose-rate results for all samples are given in Data Repository Item 2 (see footnote 1). Total 2σ errors in Table 1 are combined random and systematic errors, including instrument calibration, uncertainty in dose-rate calculation, and equivalent-dose scatter.

Aragonite samples were uranium-series dated by mass spectrometer at the Scottish Universities Environmental Research Centre following the methods of Ellam and Keefe (2007). Sample processing to preconcentrate and separate U and Th is described in detail in Burnside (2010). Ages were calculated using Isoplot/Ex rev. 2.49 (Ludwig, 2001) and the decay constants of Cheng et al. (2000). Final ages are reported in Table 1 with 2σ total analytical errors. To ensure the reproducibility of travertine ages, three samples from the greater study area were used for repeat analysis in Burnside et al. (2013). The ages reported here from the travertine mound associated with the P6/5 deposit include white-banded vein samples and a single-layered mat

sample. The range of age results is interpreted to reflect the duration of the episode of spring activity recorded in the deposit.

RESULTS

Chronostratigraphy

Seven distinct main-stem (M1–M7) Green River strath-terrace deposits were identified in the Crystal Geyser map area (Fig. 1B), with some additional fill-cut terrace levels beveled upon them (DR1 map [see footnote 1]). A relatively minor strath terrace labeled M6y (for “younger”) lies intermediate between the extensive M6 and M5 below, and this terrace has important relations, discussed in the following. The most prominent Pleistocene terraces range from 12 m (M2) to 56 m (M6) in height above the modern channel edge. The terrace treads have poorly developed desert pavements and complex calcic and gypsic soils. M1 is a series of finer-grained Holocene deposits of the river floodplain, and it includes associated travertine near Crystal Geyser with dates ranging from ca. 9 to 5 ka (Fig. 2; Burnside et al., 2013). Pleistocene terraces M2–7 have well-developed and exposed planar straths and are capped by up to 10 m of cobbly alluvium where fully preserved (Figs. 2 and 3). The deposits are clast-supported, rounded, and strongly imbricated, pebble-cobble gravel with tabular to broadly lenticular, medium bedding, and rare sand lenses. Clasts are dominated by sandstone transported from Desolation Canyon and quartzite from the Uinta Mountains over 300 km upstream. Finer-grained overland-flow deposits of local piedmont slopes interfinger with and prograde over these distinctive main-stem gravels (Fig. 2).

Luminescence age results provide stratigraphically coherent age estimates for deposi-

tion of the M6, capping P6 (“piedmont-6”) and P5, and the inset M3 terraces (Table 1). When combined with the uranium-series results from the basal P6 deposit, it is evident that the M6, M6y, and M5 terraces, which dominate the local landscape, represent a complex episode of river planation and gravel deposition from ca. 115 to 85 ka (Fig. 2). This correlates well to a similarly prominent terrace that is well dated and recorded downstream in the Grand Canyon area, where it is a thick fill terrace labeled M4 (Pederson et al., 2013). Likewise, the ca. 42 ka M3 deposit at Crystal Geyser has a well-dated analog along the Colorado River in both the neighboring Moab, Utah, area and in Grand Canyon (Jochems, 2013; Pederson et al., 2013). These initial indications that episodes of river planation and sedimentation, with intervening incision, correlate at Milankovitch time scales across the region are consistent with terrace formation being broadly driven by the effects of climate change on sediment supply and transport, rather than linked to different, specific base-level changes propagating up the river system (e.g., Bull, 1991; Hancock and Anderson, 2002; Finnegan and Balco, 2013).

Between these well-dated terraces, the M4 terrace deposit has an OSL result that is less reliable. Triplicate chemistry results confirm an anomalously high environmental dose rate for this sample, specifically due to high concentrations of uranium and thorium in the sediment and potential disequilibrium in the uranium-series decay chain relative to the other samples of Green River alluvium (DR2 [see footnote 1]). The initial age result is therefore anomalously young. The sand lens sampled in this terrace gravel lies at a relatively shallow depth of 1.7 m, within a clear gypsic B horizon of the soil profile observed there. Gypsum is generally abundant in the Mancos Shale parent material, which

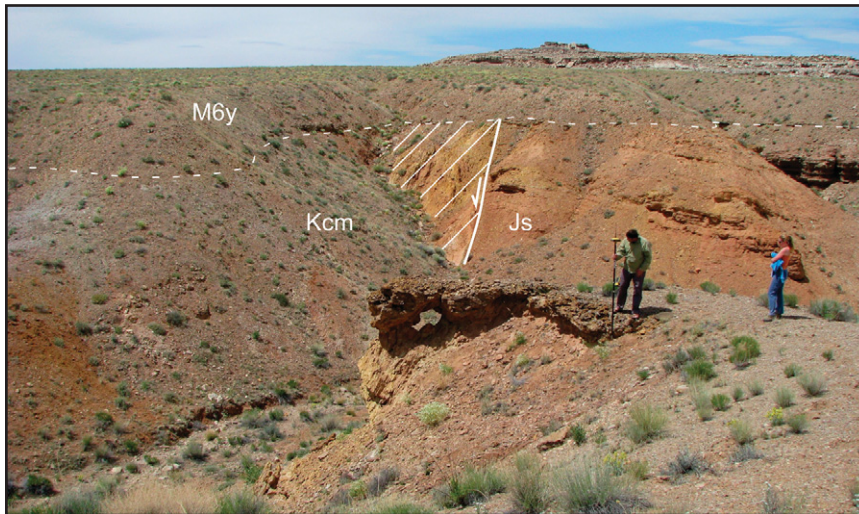


Figure 3. Photograph looking west across a gully drainage into the trace of the Little Grand Wash normal fault, here offsetting Cretaceous Cedar Mountain Formation (Kcm) against the Jurassic Summerville Formation (Js) in the footwall (hachures denote zone of fault deformation). The undeformed strath of the M6y terrace crosscuts the fault zone, indicating no measurable surface rupture over the past ~100 k.y.

is also known for elevated concentrations of uranium (Piler and Adams, 1962). This particular sample locality may have higher amounts of that parent material, and it is possible that uranium has also translocated to the depth of the OSL sample over the arid Holocene. Regardless, the modern dose rate measured is likely higher than the true time-averaged dose rate to which the sample was subjected over its longer history of burial. When we substitute the mean dose rate of all other samples in this study, the resulting age estimate of ca. 60 ka is in stratigraphic order.

Field Evidence Regarding Fault Activity

The Little Grand Wash fault is expressed in the landscape by an embayed escarpment held up by the relatively resistant Jurassic sandstones along the footwall. There is no evidence for scarps along the actual fault trace running south of this escarpment, and piedmont slopes and river-terrace treads cross the fault without topographic deflection. Field relations between the fault plane and the strath terraces of the study area provide more direct evidence that there has been no recent measurable slip on the Little Grand Wash fault. The most visible example is the undeformed basal strath of the M6y terrace overlying the trace of the fault exposed in a gully drainage (Fig. 3). Although the M6y deposit is not directly dated, it is in a landscape position just 4 m below the larger M6, which is constrained by both uranium-series and OSL ages to 115–95 ka. If the Little Grand Wash fault in this arid setting had even slow slip rates of 0.01

mm/yr, it would produce 1 m of offset over the 100 k.y. of our record and be reflected by fault-line scarps and offset of Quaternary units. It is not, and we conclude that there has been no surface rupture of the fault over the past ~100 k.y.

Likewise, the travertine mounds along the fault trace straddle the fault without being offset, and there is no offset of the internal layering of the travertine (Dockrill, 2006; Burnside, 2010). Disrupted and rotated veins and layering within the local travertine mounds have been interpreted as potential indicators of seismic activity (Shipton et al., 2004) and surface rupture (fig. 4f in Kampman et al., 2012). However, we suggest that such textures are equally likely to be due to failure of wall rock in an eruption of groundwater (Uysal et al., 2009), progressive erosion of the base of the mounds that overlie the softer Mancos Shale (Burnside, 2010), or even crystallization processes (Gratier et al., 2012). Kampman et al. (2012) hypothesized that periodic changes in CO₂ leakage from this fault relate to fault dilation from groundwater and flexural loading and unloading during Pleistocene climate changes. If so, those mechanisms also caused no vertical surface offset on the fault.

Incision History

The age and surveyed geometry of fluvial terraces can be used to reconstruct the episodic history of river planation and bed-load storage, separated by episodes of incision, over the past ~100 k.y. (Fig. 4). This plot of channel position, or grade, through time enables us to esti-

mate an overall bedrock incision rate integrated over the length of these climate-driven episodes (e.g., Bull, 1991; Pederson et al., 2006). Along the Green River at Crystal Geyser, this results in a net bedrock incision rate of ~450 m/m.y., which is the slope of the visually estimated trend line drawn in Figure 4 (a strict regression through data points is unjustified and would imply greater precision than exists). This result is similar to other surprisingly rapid trunk-river incision rates calculated in the central Colorado Plateau over the late Pleistocene and utilizing multiple age constraints (e.g., Marchetti and Cerling, 2005; Pederson et al., 2013). On the other hand, it is at least three times faster than well-constrained incision rates from Grand Canyon farther downstream (Pederson et al., 2006).

DISCUSSION

Fault Expression and Timing

The Little Grand Wash fault is clearly expressed in the landscape of the study area, marked by an escarpment at Crystal Geyser. Yet, late Quaternary fault movement has not contributed to this relief. This escarpment is, therefore, mostly the product of differential, and relatively rapid, erosion of the landscape—in this case of the weak Mancos Shale relative to the more resistant Summerville and Morrison sandstones and mudstones outcropping in the hanging-wall block. Such erosional relief from contrasting rock units juxtaposed along an inactive fault has also been documented in the Sierra Nacimiento at the southeast edge of the Colorado Plateau

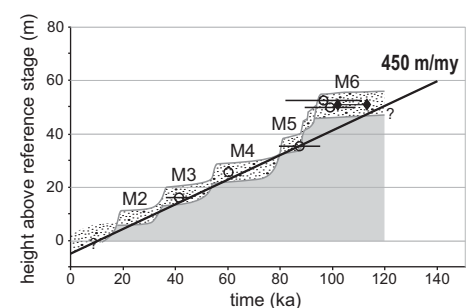


Figure 4. Plot of reconstructed Green River grade through late Quaternary time relative to modern base-flow elevation, as constrained by the surveyed terrace chronostratigraphy illustrated in Figure 2. Circles are optically stimulated luminescence (OSL) ages, with bars representing reported error, and the two connected diamonds represent range of uranium-series results. The interpreted episodes of lateral planation and terrace deposition are separated by relatively rapid incision through weak bedrock (gray). The rate of incision trending through these cycles is ~450 m/m.y.

(Formento-Trigilio and Pazzaglia, 1998). That study provided a general conclusion that is also pertinent in the central Colorado Plateau—the characteristic high-relief topography is due more to base-level fall from recent drainage integration and differential erosion of varying bedrock than from active tectonics (Formento-Trigilio and Pazzaglia, 1998; Pederson and Tressler, 2012).

Constraints for the timing of slip on the Little Grand Wash fault are limited, even with our new data. It was active sometime before 100 ka, and it offsets late Cretaceous strata. Dockrill (2006) used a database of local boreholes to confirm that there are no resolvable thickness changes across the fault from the Permian to the Cretaceous. He suggested that the fault initiated during Early Tertiary Laramide tectonism, which was prevalent across the region. A proportion of slip on the Moab fault to the east has been dated to the Early Tertiary (Pevear et al., 1997; Solum et al., 2005), supporting the possibility of Laramide movement on the Little Grand Wash fault, yet a younger component of slip is also possible.

The present-day inactivity of the Little Grand Wash fault contrasts with the active deformation of related structures across the ancestral Paradox Basin, particularly to the southeast of the study area in the Needles fault zone of Canyonlands National Park and to the east across the Utah–Colorado border region. The northern Paradox Basin is deformed into a series of roughly parallel NW-trending faults and salt-cored folds. Dissolution of Pennsylvanian salt by groundwater, and then removal by the Colorado River system, is cited as the driver of ongoing graben subsidence along the crests of the anticlines (Colman, 1983; Huntoon, 1988; Gutiérrez, 2004; Trudgill, 2011). In fact, one of these diapiric salt-cored folds is the Green River anticline, and the Crystal Geyser well was drilled where this N-plunging anticline is cut almost orthogonally by the Little Grand Wash fault (Fig. 1). Yet, the Paradox Formation evaporites are stratigraphically >1.5 km below the surface in this study area, and it is unclear from drilling records whether the fault cuts the evaporites (Shipton et al., 2004). Thus, we suggest that groundwater dissolution and salt tectonics have not been the main drivers for deformation (or the lack thereof) along the Little Grand Wash fault.

Any post-Laramide slip on the Little Grand Wash and nearby Salt Wash Graben faults may relate instead to the overall SW–NE extensional state of stress in the central Colorado Plateau, which is linked to Basin and Range rifting along the plateau margins (Wong and Humphrey, 1989). Indeed, based upon physical modeling of salt-related structures in the ancestral Paradox Basin, Ge and Jackson (1998) suggested that this

tectonic extension could drive active deformation in the region, although salt dissolution is more likely for the structures east of our study area (Gutiérrez, 2004). Related to this regional extension, ~100 km to the southwest of the study area in the east-central plateau, there are exhumed mafic dikes dated to 4 Ma by K–Ar methods (Delaney and Gartner, 1997). These have a similar average NW–SE orientation as the normal faults of the region, and it is possible the Little Grand Wash and other faults were active at this same time, responding to the extensional stress field.

Intriguingly, this possible Pliocene component of extension and faulting in the region coincides with the start of rapid erosional unloading in the central plateau (Hoffman et al., 2011; Lee et al., 2013). In fact, it has been repeatedly hypothesized that late Cenozoic base-level fall, localized erosion, and relief production have driven diapiric movement of salt elsewhere in the Paradox Basin through differential unloading (e.g., Cater, 1970; Colman, 1983; Trudgill, 2011). We suggest that broader-wavelength unloading also may have resulted in movement, including along the Little Grand Wash fault and Salt Wash Graben. The modeled pattern of isostatic rebound from late Cenozoic exhumation is roughly domal, peaking in the central plateau and diminishing proportionally to its edges (Callahan et al., 2006; Karlstrom et al., 2012; Lazear et al., 2013). This arching pattern of enhanced rock uplift across the plateau would enhance extension and could have inspired slip along regional normal faults, accommodated by salt motion at depth. This is analogous to the effects of similarly broad and domal rebound in other regions due to glacial unloading (Muir-Wood, 2000). This new hypothesis links a component of fault deformation to the broader regional history of erosion and incision.

Regional Patterns of River Incision

The river incision rate of 450 m/m.y. at Crystal Geyser over late Quaternary time is three times faster than the typical western interior U.S. average of 150 m/m.y. (Dethier, 2001), but it is consistent with the recently recognized bull's-eye pattern of rapid incision in the central Colorado Plateau (Pederson et al., 2013). Given that this relatively rapid incision is not linked to active local faulting, broader sources of base-level fall are required. In terms of active uplift, Pederson et al. (2013) pointed out that fast incision here in the central plateau is inconsistent with recently proposed mantle-driven uplift at the SW flank of the plateau and associated downward tilting of the central and NE plateau (Moucha et al., 2009; van Wijk et al., 2010; Levander et al., 2011; Karlstrom et al., 2012).

Instead, this bull's-eye is interpreted to reflect a regionalized feedback between erosional exhumation and the flexural-isostatic rebound mentioned earlier. Indeed, thermochronology results from just east of Crystal Geyser along the Book Cliffs and in the northern canyonlands confirm over 3 km of exhumation in the past ~5 m.y. (Hoffman et al., 2011). This feedback of erosion and rock uplift may drive enhanced incision in the central plateau as well as extension, but it was ultimately initiated by the 5–6 Ma integration and base-level fall of the Colorado River propagating upstream from the plateau edge west of Grand Canyon (e.g., Pederson et al., 2002; Dorsey et al., 2007).

Rapid incision in the very broad-valley landscape around Crystal Geyser may seem contrary to expectations at first, in that there is typically an intuitive correspondence among steep rivers, high canyon relief, rapid incision, and active uplift. Yet, local relief and tectonic activity are not always coupled. At Crystal Geyser, the rapidly incising Green River has a relatively low gradient and low energy expenditure (Fig. 5; Pederson and Tressler, 2012), and the entire Labyrinth Canyon just downstream lacks any named rapids. Below Cataract Canyon, the Colorado River is likewise low in gradient, yet it has high incision rates like that at Crystal Geyser (Fig. 5; Pederson et al., 2013). These low-energy, central plateau reaches coincide with a sequence of Jurassic and Cretaceous shales and sandstones at river level that are of low strength and that provide little coarse bed material to the channel. Despite this, abundant tools for river incision do exist, having been transported from Desolation Canyon and farther upstream, as evident from the gravel-clast types of the terrace alluvium in the study area. Hard tools on soft rock accomplish significant incision, as well as lateral planation, forming prominent strath terraces (e.g., Montgomery, 2004; Johnson et al., 2009). Overall, the Green River here has a channel gradient set by a relatively thin mantle of bed load in transport, which, although gentle, is more than adequate to achieve the required incision rate through weak bedrock.

Upstream in the Desolation Canyon knick zone, the river steepens where it crosses the Book and Roan Cliffs (Fig. 5). Despite this steeper gradient and the deep canyon, there is evidence that incision rates actually may be much slower than at Crystal Geyser. Darling et al. (2012) reported an incision rate a full order of magnitude slower (43 m/m.y.) at the mouth of Tabyago Canyon near the head of Desolation Canyon (Fig. 5), based upon an isochron cosmogenic-burial age of 1.48 Ma on a terrace deposit in a similar landscape position as the M6 terrace at Crystal Geyser. This is only a single age result based upon three clasts in that terrace deposit, and poten-

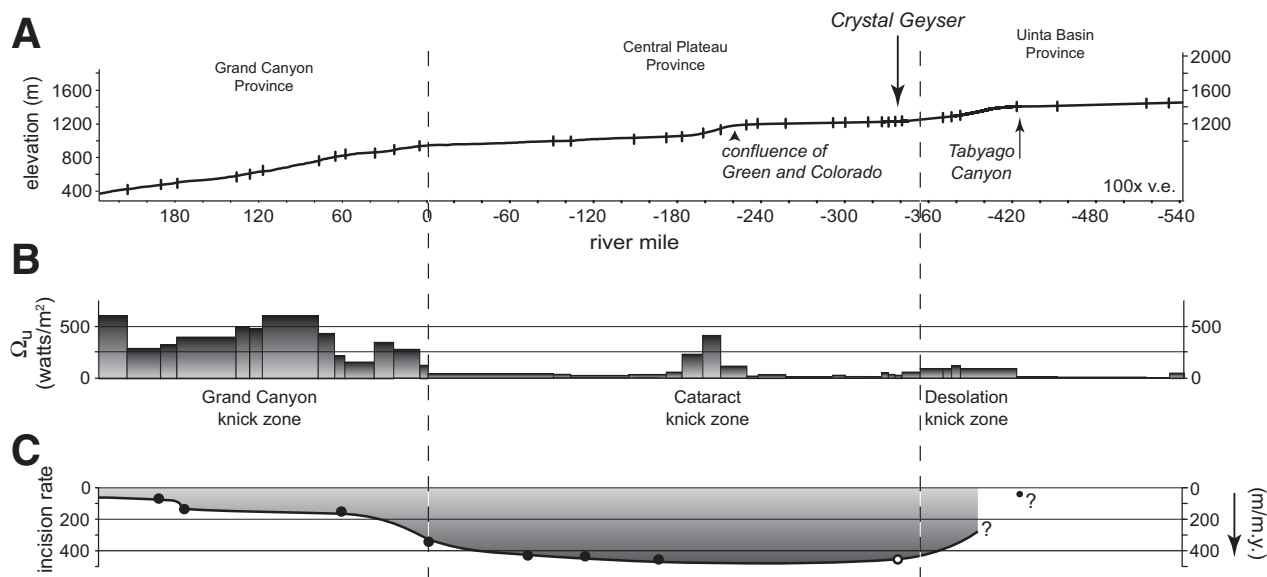


Figure 5. (A) Longitudinal profile of the Green-Colorado River system starting where the Green River leaves the Uinta Mountains and crosses the Uinta Basin, through the Desolation knick zone, and past Crystal Geyser to the confluence of the Green and Colorado Rivers at the head of Cataract Canyon, and then through Glen Canyon and finally the Grand Canyon knick zone. Tick marks bound reaches defined by bedrock substrate. (B) Reach-averaged unit stream power from Pederson and Tressler (2012). (C) Trend of comparably calculated late Quaternary river incision rates (larger black dots) from Pederson et al. (2013), with the white-centered data point being the result for Crystal Geyser. Note the lack of correspondence between the broad-wavelength pattern of incision rate and shorter variations in river steepness or energy, with the most rapid regional incision occurring in broad, low-energy reaches like Crystal Geyser. The potential decrease in incision rate through the Desolation knick zone is suggested by the longer-time-scale results of Darling et al. (2012) at Tabyago Canyon (smaller black dot), consistent with the interpretation that the knick zone potentially reflects a transient wave of incision in the system. V.E. — vertical exaggeration.

tial sources of error in this cosmogenic-dating approach include the fact that those clasts may share a significant previous history of episodic burial and transport. Furthermore, this low incision rate was calculated over a much longer time span than ours at Crystal Geyser, and therefore the difference may be partly due to averaging rates over longer variations or hiatuses in processes (Gardner et al., 1987).

Recognizing the contrast between their older burial ages and other younger terrace chronostratigraphies in the region, Darling et al. (2012) suggested that river incision across the region may have greatly increased in rate at some point in the Pleistocene. Alternatively, Pederson and Tressler (2012) suggested that the Desolation knick zone may reflect a wave of incision passing through the trunk drainage system, consistent with rapid incision near the mouth of the canyon and slow incision above (Fig. 5). Regardless of the cause, whether due to changes over space or time, the prospect that incision rates radically decrease across the Desolation Canyon knick zone is very intriguing. Further study documenting the regional history of river incision is needed to confirm such patterns, as well as to refine models of transience in river-profile evolution (e.g., Riihimäki et al., 2007; Cook et al., 2009). In summary, the high incision rate and inactive faulting we record at

Crystal Geyser over the past 100 k.y. may represent just a steady snapshot within a longer, complexly changing and linked late Cenozoic history of erosion and deformation.

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