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CORRESPONDENCE: lon.abbott@colorado.edu

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# Rates of river incision and scarp retreat in eastern and central Grand Canyon over the past half million years: Evidence for passage of a transient knickzone: REPLY

Lon D. Abbott<sup>1</sup>, Craig Lundstrom<sup>2</sup>, and Chance Traub<sup>3</sup>

<sup>1</sup>Department of Geological Sciences, University of Colorado, 399 UCB, Boulder, Colorado 80309, USA

<sup>2</sup>Department of Geology, University of Illinois Urbana—Champaign, 1301 West Green Street, Urbana, Illinois 61801, USA

<sup>3</sup>Environmental Studies Program, Prescott College, 220 Grove Avenue, Prescott, Arizona 86301, USA

Crow et al. (2014) and Abbott et al. (2015) were the first studies to use river terrace age data to extend the incision record for eastern and central Grand Canyon beyond ca. 400 ka. An accurate understanding of Grand Canyon's long-term incision history has obvious geomorphic significance, but it also has geodynamic importance in light of recently proposed models for late Cenozoic, mantle-driven surface uplift on the Colorado Plateau (e.g., Moucha et al., 2008; 2009; Roy et al., 2009; Levander et al., 2011; Roberts et al., 2012; Karlstrom et al., 2012; Becker et al., 2014). Crow et al. (2014) interpreted their incision results as strong support for the Karlstrom et al. (2007; 2008) model of temporally steady but spatially variable Grand Canyon incision since at least 3–4 Ma, which they attributed to mantle-induced surface uplift. By contrast, Abbott et al. (2015) concluded, based on data from two locations, that the incision rate in eastern and central Grand Canyon was rapid between ca. 500–400 ka during passage of a transient knickzone and subsequently decreased to the rate measured by previous workers (Crow et al., 2014; Pederson et al., 2002; 2006; Karlstrom et al., 2007). In their Comment, Crow et al. (2015a) raised four objections to our conclusions: (1) Our study did not constrain the ancient elevation of the Colorado River at either location; (2) Our U/Th ages at the Hermit Creek study site (river mile [RM] 96) do not record the depositional age of the strath terrace; (3) Our transient knickzone model is incompatible with seven “well-dated” river gravels presented by Crow et al. (2014); (4) The ~340 m-high knickpoint implied by our model is “unreasonable” and our proposed incision rate during knickzone passage is 2–8 times greater than the highest known knickpoint-controlled bedrock incision rate in the southwestern U.S. We discuss each of these criticisms in turn.

## PALEO-COLORADO RIVER HEIGHT IS UNCONSTRAINED

In their Comment, Crow et al. (2015a) argued that the ca. 520 ka 159-Mile Dikes, which we used to constrain the incision rate at RM 159, were intruded into an extant Muav Gorge and that the river terrace we used to constrain incision rate at RM 96 does not contain Colorado River gravels.

## The 159-Mile Dikes at RM 159

We agree with Crow et al. (2015a) that the presence of preexisting joints might have influenced intrusion of the 159-Mile Dikes. Whether or not the dikes exploited such joints during ascent is, however, a question that can only be answered by a detailed structural study, as noted by Delaney et al. (1986), who discussed an “unexpected” diversity of relations between dikes and joints at three separate Colorado Plateau locations. They concluded, “the mere presence of dike-parallel joints in host rock adjacent to the dike should not be accepted as evidence that the magma intruded along older joints” (p. 4935). Beyond that, the joint orientations Billingsley (2000) mapped near the 159-Mile Dikes are all oblique to the dike trend. Given these considerations, it is clear that a focused structural study on the 159-Mile Dikes and adjacent joints is needed in order to resolve the issue of joint involvement in the dike emplacement process.

In order to further support their argument that the 159-Mile Dikes intruded into an extant canyon, Crow et al. (2015a) claimed that “numerous modern examples” show that dikes can propagate across significant relief. Their one citation, though, is Tilling (1987). That paper's sole mention of dike emplacement directly contradicts Crow et al.'s (2015a) statement that fissure eruptions during the 1973 Mauna Ulu eruption occurred “on the flanks and rims of (Pauahi) crater but not at its bottom.” Tilling (1987) wrote that the “first eruptive fissure to open was located in the bottom of the deep west pit of the composite Pauahi Crater” (p. 13,726).

Although Tilling (1987) said nothing further about dike intrusion during the 1973 Mauna Ulu eruption, Tilling et al. (1987) did. We reproduce as Figure 1 their figure 16.3, which shows dikes that intersected both the Pauahi and Hiiaka craters during two phases of the 1973 Mauna Ulu eruption. In our paper, we emphasized that our interpretation of the 159-Mile Dikes as intruding prior to canyon incision hinges on the fact that the dikes *crosscut* the Muav Gorge and are coplanar on both sides of the Colorado River. We pointed out that it is much more difficult for an igneous dike to crosscut a river gorge than to intrude one steep volcanic flank. Figure 1 illustrates that no dike crosscuts the steep-walled Pauahi Crater (nor Hiiaka Crater), as Crow et al. (2015a) implied.

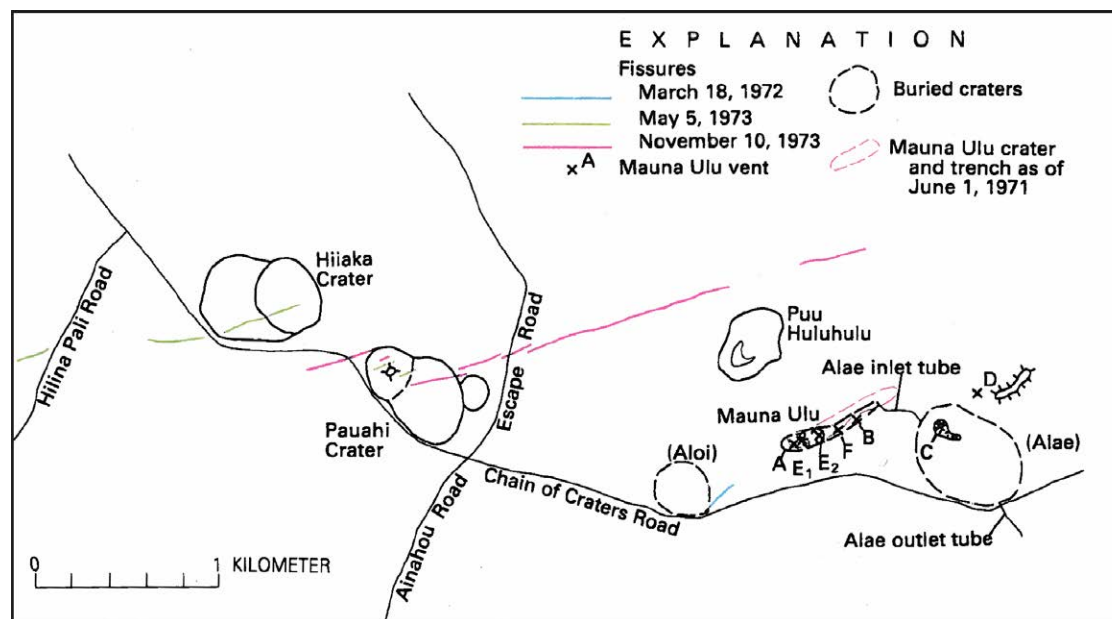


Figure 1. Sketch map of the volcanic dikes that propagated into the Pauahi and Hiiaka craters (red and green lines) during the 1972–1974 Mauna Ulu eruption at Kilauea volcano, Hawaii. Note that the dikes cut one flank of each crater but *do not cross-cut* either crater from one crater wall to the other. From Tilling et al., 1987 (their fig. 16.3).

This example is not a strong argument against our pre-incision interpretation of the 159-Mile Dikes.

By contrast with Crow et al.'s (2015a) argument, Hamblin (1994, p. 23) agreed with Dutton (1882), who considered it “manifestly impossible for a basaltic lava to rise hundreds to thousands of feet through solid limestone with one edge protruding laterally from the face of the valley wall.” Billingsley (2000) used this reasoning to conclude that the 159-Mile Dikes intruded prior to the cutting of the Muav Gorge. Crow et al. (2015a) presented another alternative: that the dikes intruded into a pile of sediments that accumulated in a lava-dammed lake and were subsequently eroded away. Although we must admit this possibility, we note that Crow et al. (2015b) emphasized that no sediments plausibly deposited in a lava-dammed lake have been found *anywhere* in Grand Canyon. Given the absence of positive evidence for lake sediments, the argument that the 159-Mile Dikes intruded into an extant, sediment-filled Muav Gorge is ad hoc. We concur with Dutton (1882), Hamblin (1994), and Billingsley (2000), and conclude that the Colorado River has incised Muav Gorge by ~340 m since the ca. 520 ka intrusion of the 159-Mile Dikes.

### The Hermit Creek Paleofan at RM 96

Crow et al. (2015a) argued that the Hermit Creek paleofan at RM 96 contains no verified Colorado River gravel. They did not take issue with our ob-

servation that short-distance transport in Colorado River tributaries is insufficient to round the pebbles present in several outcrop P1 lenses (see p. 645 of Abbott et al., 2015). Nor did they address our favorable comparison of those lenses’ lithology with that of terrace gravels near Tanner Rapid that Anders et al. (2005) and Crow et al. (2014) identified as Colorado River gravel (see our fig. 13). Importantly, they also chose not to address our point that even if none of the gravel in outcrop P1 was deposited by the Colorado River, that doesn’t change our conclusion that the river’s incision rate slowed through time (see p. 656 of our paper).

We argued that the Hermit paleofan’s sub-horizontal beds require that the fan accumulated prior to the cutting of the Inner Gorge (see our p. 645 and figs. 9 and 14). Crow et al. (2015a) posit, instead, that the Hermit paleofan accumulated at the edge of a lava-dammed lake, using the modern Spencer Canyon debris fan at the edge of Lake Mead as an analog. This is possible only if Hermit Creek transported outcrop P1’s well-rounded pebbles, which, as discussed in the preceding paragraph, we consider unlikely. Furthermore, it seems likely that if the Hermit paleofan formed at the edge of a lake, some fine-grained lake sediment would be preserved within the abundant travertine that was precipitating on the fan. No such fine-grained sediment is present in any of outcrops P1–P4. In light of that absence, we conclude that Crow et al.’s (2015a) hypothesis that the Hermit paleofan was deposited on the shore of a lava-dammed lake (with the Colorado River channel lying far below) lacks sufficient support.

## ■ OUR U/Th AGES DO NOT RECORD THE AGE OF DEPOSITION ON THE HERMIT FAN

Crow et al. (2015a) contended that our ca. 500 ka U/Th ages record young travertine infilling rather than the age of gravel deposition on the Hermit paleofan. We considered and rejected this possibility based on textural evidence (see p. 647–649 and fig. 15 of Abbott et al., 2015) and because Crow et al.'s (2015a) model requires that texturally cryptic travertine re-precipitation events occurred simultaneously in three hydrologically isolated outcrops (see p. 656–657 of our paper). We consider such an occurrence far less likely than simultaneous deposition of first-generation travertine by multiple springs at different locations within the growing, hydrologically continuous Hermit paleofan.

## ■ OUR MODEL IS INCOMPATIBLE WITH SEVEN “WELL-DATED” TRAVERTINE SAMPLES

On their figure 1, Crow et al. (2015a) plotted the data of Crow et al. (2014) and Abbott et al. (2015) on a longitudinal profile of the Colorado River through Grand Canyon. They highlighted seven of their data points that they considered both “well-dated” and incompatible with our transient knickzone model. As we discussed on p. 656 of our original paper, we consider only two of these seven data points to be “well dated” (the two purple 467 ka points on their figure 1). Both points are compatible with our model. Given Crow et al.'s (2014) reported age uncertainties, these two points could be 80–110 ka younger than the Hermit paleofan or the 159-Mile Dikes. Knickpoint incision rates are sufficiently rapid (see the following section) that the river could well have incised several tens to hundreds of meters during that time interval, thereby reconciling the data from both studies.

Figure 2 illustrates how poor the age constraints are for the other five points Crow et al. (2015a) argued are incompatible with our transient knickzone model. Crow et al. (2014) reported age uncertainties of  $\pm 440$  ka for point 880 and  $\pm 420$  ka for point 980 on Crow et al.'s (2015a) figure 1. The age of point 1272, which appears to be the sole anchor for the hypothesized 1.5 Ma longitudinal profile, is reported as  $1272 \pm 605$  ka. Error bars for the other two points are  $623_{-162}^{+78}$  ka and  $651_{-82}^{+151}$  ka (Crow et al., 2014). As we illustrate on Figure 2, passage of a transient knickzone could lower the elevation of the Colorado River by hundreds of meters during the time encompassed by these error bars. For this reason, the reconstruction of longitudinal profiles from the older terrace data is misleading.

Even beyond the significant problems these large age uncertainties present for Crow et al.'s (2015a) ability to convincingly reject our transient knickzone hypothesis, still others are raised by the inherent unreliability of U/Th ages older than 600–650 ka (see Abbott et al., 2015 p. 640–641) and the fact that  $^{234}\text{U}$  model ages (such as that of point 1272) are suspect because one must assume, a priori, the  $^{234}\text{U}/^{238}\text{U}$  initial ratio (Abbott et al., 2015, p. 641 and 656). Consider-

ing these numerous limitations, the terraces Crow et al. (2015a) presented on their figure 1 are anything but “well dated” and are not grounds for rejection of the transient knickzone model.

## ■ KNICKZONE HEIGHT AND INCISION RATE ARE BOTH “UNREASONABLE”

Crow et al.'s (2015a) final objections to our transient knickzone model are that it requires both an “unreasonably” tall knickpoint and an equally unreasonable incision rate. Here we examine both objections, in turn.

We place the Colorado River at RM 159 at about the top of the Redwall Limestone (~914 m elevation) after intrusion of the 159-Mile Dikes at  $517 \pm 16$  ka. Karlstrom et al. (2007) dated a terrace at RM 181.6 as  $607 \pm 48$  ka, slightly older than the 159-Mile Dikes. Crow et al. (2015a) concluded that the river stood at ~580 m there at ca. 607 ka (see blue point 607 on their fig. 1). If our transient knickzone hypothesis is correct, the river dropped almost 340 m over 36 km (i.e., ~9.5 m/km). Considering that the modern Gunnison River is much steeper, dropping ~18 m/km through the Black Canyon (a distance of ~19 km; Hansen, 1987), we argue that this gradient is not “unreasonable.” Note, further, that the modern Gunnison River drops 8 m/km through an 80-km reach and has a maximum gradient of 45 m/km in the 3-km stretch between Pulpit Rock and Chasm View in Black Canyon of the Gunnison National Park (Hansen, 1987).

Crow et al. (2015a) also claimed that our incision rates are 2–8 times higher than any previously calculated rates in the southwestern U.S., implying them to be unreasonable. We calculated an average incision rate of 461–574 m/m.y. at RM 96 and a rate of 703–749 m/m.y. at RM 159 over ca. 500 ka duration. Donahue et al. (2013) reported a maximum incision rate of 640 m/m.y. in Black Canyon of the Gunnison over the past 640 ka, based on the elevation of a sample of Lava Creek B ash at Chukar Ridge. Our rates are lower than, or at most, 20% higher than those reported by Donahue et al. (2013), despite being averaged over a shorter time span. Therefore, we see nothing unreasonable about them.

Incision rates averaged over comparatively long durations, such as those cited above, are typically the only ones possible to obtain. However, it is likely that much higher transient incision rates occurred over shorter durations during knickzone passage. Fortunately, our RM 96 site includes two outcrops (P1 and I2) that allowed us to calculate a high transient rate, which is 1000–4000 m/m.y. (see p. 649 of our paper). This transient rate is 1.5–6 times higher than Donahue et al.'s (2013) maximum rate, making it the likely cause for Crow et al.'s (2015a) objection. However, this very high rate is averaged over a 47–177 ka duration (the limits of the U/Th age uncertainties for P1 and I2), much shorter than the 640 ka duration for the Donahue et al. (2013) rate. The different durations make direct comparisons between these rates inappropriate (e.g., Gardner et al., 1987); it is almost certain that the Chukar Ridge rate (in Black Canyon) was faster than the 640 m/m.y. average during some shorter time interval, but the lack of a second age and height control point precludes any determination of what that transient rate actually was.

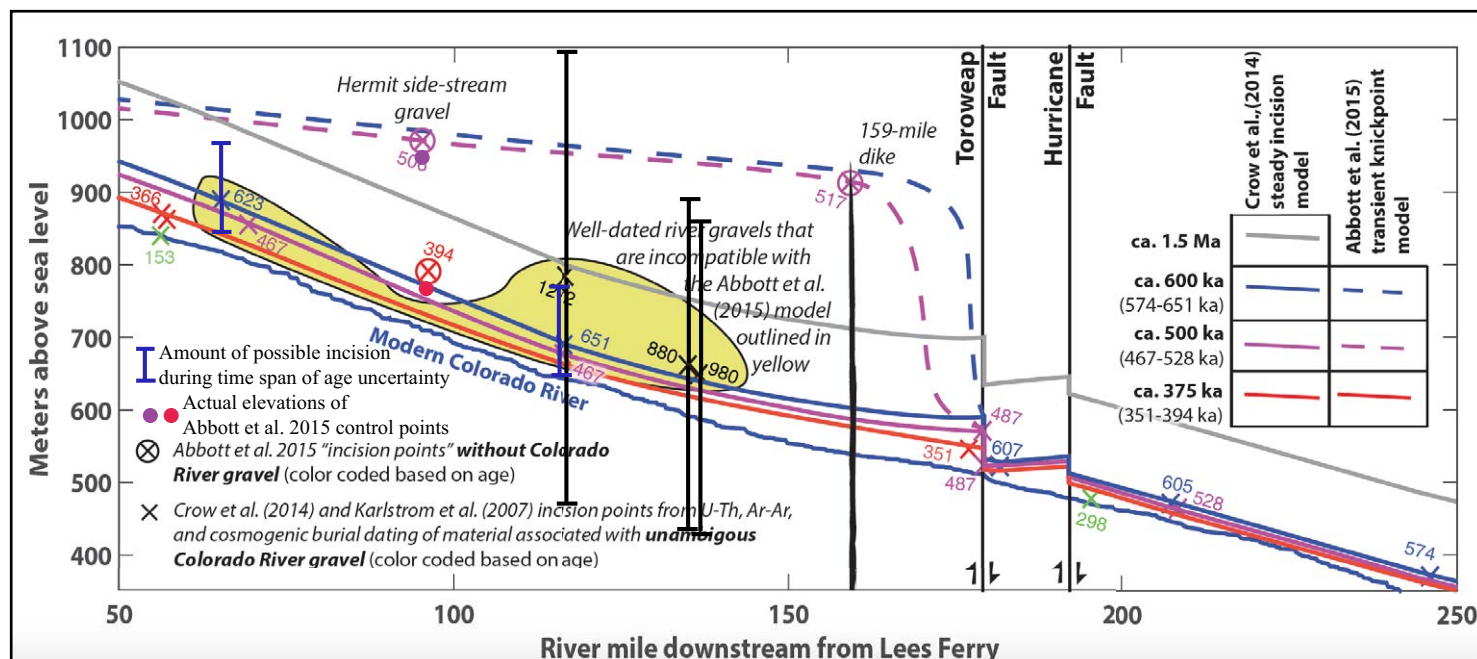


Figure 2. Crow et al.'s (2015a) figure 1, with error bars added to illustrate the amount of incision that would occur during the time span of the age uncertainties reported by Crow et al. (2014), assuming an average incision rate of 519 m/m.y. (the average rate determined by Abbott et al., 2015 at RM 96). Error bars are shown for five of the seven "well-dated" river gravels that Crow et al. (2015a) argued invalidate the Abbott et al. (2015) transient knickzone model (i.e., the yellow region). No error bars are plotted for the two purple "467" points because the errors are only slightly larger than each purple "X". The error bars illustrate that Crow et al.'s (2015a) longitudinal profiles are merely conjecture. The red and purple dots show the true elevations of the Abbott et al. (2015) control points, which Crow et al. (2015a) plotted incorrectly.

Western Grand Canyon's lava dams do, however, record very fast transient incision rates. Hamblin (1994) concluded, based on the K-Ar age dating available to him at the time, that 13 lava dams impounded the Colorado River below RM 179 during the past ca. 1.8 Ma. He pointed out that a knickpoint formed at the base of each dam and propagated headward, thereby breaching the dam. Crow et al. (2015b) revised Hamblin's mapping of dam remnants and used  $^{40}\text{Ar}/^{39}\text{Ar}$  dating to conclude that 17 separate dams have plugged the western Grand Canyon since ca. 850 ka.

It is unclear how many of the lava flows that entered western Grand Canyon resulted in durable lava dams (i.e., ones that didn't immediately fail catastrophically) (see Hamblin, 1994; 2003; Fenton et al., 2004, 2006; Crow et al., 2008, 2015b). However, two spots exist where lava dam impoundment diverted the river, causing it to carve new canyons through the Paleozoic bedrock (~250 m and ~150 m deep, respectively). These two locations provide strong evidence of rapid transient river incision that far exceeds the ~50–75 m/m.y. average rate determined by Karlstrom et al. (2007) or the ~101 m/m.y. rate Crow et al. (2014) calculated for western Grand Canyon during the past ca. 600 ka.

The first of these locations is Buried Canyon (RM 183, see Hamblin, 1994, fig. 40), where a 200 m-high,  $524 \pm 34$  ka basalt dam fills the entire paleochannel of the Colorado River (Crow et al., 2015b). The river cut a new channel slightly farther south through Paleozoic bedrock. The modern river stands ~50 m below the base of the paleochannel. The second location, at RM 194, is a paleochannel filled with 110 m of sediment that Fenton et al. (2004) attributed to an outburst flood at ca. 200 ka. The base of the paleochannel is ~40 m above the modern river. Therefore, the river incised through 200 m of bedrock at Buried Canyon between ca. 525 and ca. 200 ka at an average rate of 615 m/m.y. over 325 ka. The river then initiated another rapid incision episode in response to blockage by a later lava dam, cutting through 150 m of bedrock at RM 194 during the past 200 ka, which translates to an average incision rate of 750 m/m.y.

But the transient incision rate during passage of the Buried Canyon knickpoint was considerably faster still. Hamblin (1994) mapped a veneer of basalt overlying the Bright Angel Shale just above river level on the south wall of the Buried Canyon paleochannel. Crow et al. (2015b) called this the 183.4-mile

remnant, which they dated at  $492 \pm 32$  ka (their p. 1329). These data reveal that, after blockage by the Buried Canyon lava dam at  $524 \pm 34$  ka, the Colorado River cut a new, 200 m-deep channel through Paleozoic bedrock in less than 100 ka. This requires a *minimum* incision rate during transient knickpoint passage of 2000 m/m.y., comparable to our rate of 1000–4000 m/m.y. at RM 96 over the same 100-ka duration.

The above analysis shows that neither our proposed knickpoint height nor its associated incision rate is unreasonable. Other data also support the presence of such a knick. Polyak et al. (2008) concluded that their proxy incision rate data reveal recent knick passage and we pointed out that Crow et al.'s (2014) data likely reveal a slowing of incision rate toward the present (Abbott et al., 2015, p. 656).

Several mechanisms could explain why such a knick developed. Down-to-the-west throw on the Hurricane and Toroweap faults has lowered base level west of RM 190 by ~75 m since 500 ka (e.g., Fenton et al., 2001; Karlstrom et al., 2007), which could initiate a knickpoint. The knickpoints that sequentially removed as many as 17 separate lava dams (Crow et al., 2015b) also likely migrated upstream. Even broad wavelength, mantle-induced surface uplift could trigger a transient knick. Karlstrom et al. (2008) and Crow et al. (2014) inferred a temporally steady Grand Canyon incision rate and argued that that steady rate suggests mantle-driven surface uplift is responsible for incision. But Whipple and Tucker (1999) demonstrated that a spatially broad change in elevation such as this would trigger migration of a transient knickpoint prior to establishment of steady-state incision. Becker et al. (2014) argued that the southern edge of the Colorado Plateau has experienced dynamic uplift within the past million years; if true, such a mantle-induced change in surface height could also trigger a transient knick. So too would the ~350 m of rock uplift that Pelletier's (2010) numerical modeling suggested has occurred in Grand Canyon during the Plio-Quaternary due to the isostatic response to cliff retreat.

The modeling done by Cook et al. (2009) revealed how complex the incision rate history recorded by river terraces will become with the passage of even a single knickpoint, especially when bedrock erosion resistance is variable, as is the case along the Colorado River. Pelletier's (2010) numerical model added base level perturbations due to slip along the Hurricane and Toroweap faults, revealing a yet more complicated incision rate history (see his fig. 13). Adding to this the expectation that every late Quaternary lava dam emplaced since ca. 850 ka would trigger its own transient knick, a migrating knickzone model seems far more likely than does the steady incision model of Karlstrom et al. (2008) and Crow et al. (2014) to explain the long-term incision history of Grand Canyon.

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