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Differential incision of the Grand Canyon related to Quaternary faulting—Constraints from U-series and Ar/Ar dating: Comment and Reply

COMMENT

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Pederson et al. (2002) present bedrock incision rates of the Colorado River at three sites in the Grand Canyon. From west to east, these sites and rates (averaged over the past 300 to 500 k.y.) are Granite Park, 72–92 m/m.y.; Toroweap, 133 ± 16 m/m.y.; and Eastern Canyon, 135 ± 17 to 144 ± 18 m/m.y. Granite Park is located ~10 fault-normal km west of the Hurricane fault, which in turn is located ~15 km west of the Toroweap fault. Toroweap is located just east of the Toroweap fault, where it crosses the Colorado River, while Eastern Canyon is ~110 km east of the Toroweap fault, at the mouth of the Little Colorado River (Pederson et al., 2002, their Figs. 1 and 2). The Hurricane and Toroweap faults are down-to-the-west normal faults, with mid to late Quaternary slip rates of 70–170 and 70–180 m/m.y., respectively (Fenton et al., 2001), which Pederson et al. (2002) propose as the cause of the east-west difference in bedrock incision rates across these faults. We agree that these faults can affect the nearby Granite Park and Toroweap incision rates; we disagree that this is possible at the Eastern Canyon locality.

More generally, the Hurricane and Toroweap faults can do little to perturb erosion rates anywhere along the Colorado River more than several tens of kilometers away from these faults, either upstream or downstream. On an earthquake-by-earthquake basis, the vertical displacements arising from crustal normal faults attenuate with a horizontal (away-from-the-fault) distance metric determined by the depth of faulting or equivalently, in most cases, the seismogenic thickness. Typically, this is ~15 km in the western United States. Elastic dislocation models of elevation data for the Borah Peak, Idaho, earthquake (18 October 1983; M = 7.3), the best documented case of crustal normal faulting in this region, clearly show this effect (Barrientos et al., 1987), as do the 1959 Hebgen Lake and 1954 Dixie Valley–Fairview Peak earthquakes. Over the course of many earthquakes spanning hundreds of thousands of years or more, these elastic dislocation solutions are additive, until such time as the strength of the locally deformed crust is exceeded. New faults are then formed, or reactivated, and the Hurricane and Toroweap faults are probably related in this way. The spacing between these faults will also be measured in terms of a seismogenic thickness or two, as is the spacing of the basins and ranges to the west.

Figure 1 shows the topography of the Hurricane and Toroweap faults just south of their intersection with the Colorado River, in both plan (top) and in elevation (bottom), and clearly reveals the very local effect these faults have on the topography. This topography bears little resemblance to either of the essentially block-motion tectonic models proposed in Pederson et al.'s (2002) Figure 3; neither does it provide any rationale for the nearly coincident incision rates at Toroweap (which should be affected by faulting) and at the Eastern Canyon locality (which should not be).

Any of these faulting models, however, provide for a steepened Colorado River gradient in the vicinity of the Hurricane and Toroweap faults, so it is a surprise to discover that just the opposite is happening: Pederson et al.'s (2002) Figure 2 reveals a slight but significant flattening of the river gradient in the vicinity of these two faults. Better seen in Leopold (1969, their Fig. 97), this reach of the river is the rising limb of a pronounced bulge in the river profile that extends for some 90 river miles (160 to 250). This local river-profile convexity requires an active and powerful process capable of not only overprinting any signature of faulting but also capable of defeating the river's otherwise monotonic trajectory to base level. Leopold (1969) shows not only the profile bulge in the western canyon, but a second in the eastern canyon, between river miles 40 and 80, possibly extending to river mile 100. The eastern canyon profile bulge is far removed from the tectonic and volcanic processes that should be affecting the western canyon profile bulge. Table 5 of Webb et al. (1999) reveals that all but one of the 14 largest debris flow fans in the Grand Canyon, as ranked by area, occur within one of these two reaches of the Colorado River, and it is likely that debris-flow activity is a principal cause of the two river-profile bulges: as a matter of chance alone, this would be a coincidence with probability of <1 in 10^5.

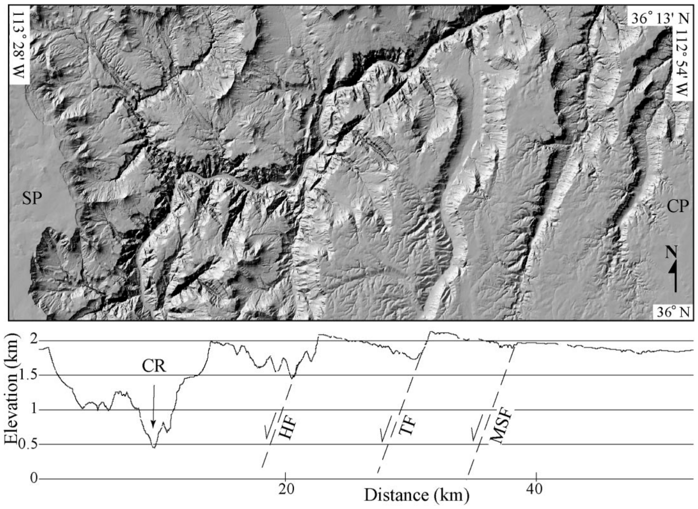

Figure 1. Plan view (top) and elevation profile (bottom) along 36°N, which forms southern boundary of the plan view of Hurricane and Toroweap faults in western Grand Canyon region, Arizona, from U.S. Geological Survey 10 m resolution digital elevation model. From west to east, the elevation profile begins on Shivwits Plateau (SP); crosses Colorado River (CR), Hurricane fault (HF), Toroweap fault (TF), and Mohawk Stairway fault (MSF); and ends on Coconino Plateau (CP).

An important implication of the preceding paragraph is that all three of the Pederson et al. (2002) incision-rates sites are in places where the riverbed would seem to be aggrading, not incising. The amplitudes of these river-profile convexities are substantial, ~15 to 30 m, comparable to the elevation differences used in Pederson et al. (2002) to determine incision rates. These convexity amplitudes, however, are not accounted for by the Pederson et al. (2002) ''pool-depth'' corrections, which leave the thickness of debris fill between river bottom and channel bottom unknown, at times both past and present. The temporal durability of these river-profile convexities is also unknown, adding further uncertainty to incision-rate estimates in these reaches of the river.

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REPLY

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In our paper, we confirmed that the Colorado River has incised the Grand Canyon at significant and spatially variable rates over the middle–late Quaternary and hypothesized that this variability in incision may be due to normal faulting, in that subsidence near the hanging wall of the fault locally reduces incision rates. Hanks and Blair, likewise, have two main comments. The first is about the pattern of offset related to regional normal faulting, which does not seem to conflict with the statements in our paper. The second addresses possible errors in our incision rate calculations related to variations along the Colorado River's long profile. We stand by our method of calculating bedrock incision and believe it provides the best estimates possible at this time (and note that even if Hanks and Blair's criticism is valid, our results and interpretations would not be greatly affected).

Hanks and Blair apparently agree with us that the lower incision rates west of the Hurricane-Toroweap fault system can be explained by the reduction of incision due to west-down slip on these faults. They state that this faulting would not be expected to affect incision rates in the eastern Grand Canyon. We agree, and this was one of the main points of our paper: Contrary to many places discussed in the recent geomorphic literature, the Grand Canyon is a situation where faulting does not drive (increase) incision rates upstream (e.g., eastern Grand Canyon), but instead, through subsidence, decreases incision rates in the hanging wall area downstream of the faults (e.g., Granite Park locality). Hanks and Blair state that incision rates at the locality just a few kilometers upstream of the Toroweap fault should be affected by faulting, though they do not state how or why. It seems they assume that any surface or absolute displacement, regardless of geometry, will steepen river gradient and affect long-term stream incision upstream. This is not always the case—again, one of our main points. Integrated over a time span longer than glacial-interglacial climate changes, the Colorado River in the Grand Canyon has been incising bedrock both upstream and downstream of the faults as a result of effective base-level fall farther downstream.

Their comment about normal fault spacing and seismogenic character, however correct, is not directly relevant to our paper. First, topography only equates to fault displacement if there is zero erosion, which is certainly not the case in the Grand Canyon. Second, our Figure 3 is not a ‘‘block motion'' tectonic model, but rather a simple geometric illustration of how fault slip may either drive upstream or reduce downstream incision. In the first paragraph of our paper's discussion, we suggested that displacement may decrease away from the fault into the hanging wall, just as Hanks and Blair imply. We had only a single incision rate on the downstream side at the time of the paper, and hence our data could not address this issue. We are continuing to date basalt flows and estimate incision rates across the faults, which should help answer the questions about footwall uplift, possible listric fault geometry, and strain accumulation during faulting that may be underlying Hanks and Blair's comments.

The second part of Hanks and Blair's comment addresses large-scale convexities in the longitudinal profile of the Colorado River through the Grand Canyon. They suggest that the reach-scale convexities in the profile of the river may be the result of spatially variable debris-flow activity creating very broad reaches that are aggrading relative to neighboring reaches. Hanks and Blair point out that if local aggradation is happening, we would be underestimating the depth to bedrock beneath the river and thus our bedrock incision estimate would be too low. We stand by our method as a thoughtful and conservative approach that tries to compare apples to apples (the height of bedrock straths to an estimate of present-day bedrock) and that considers the complexities of fill terraces. There are several possible controls on the Colorado River's long profile depending upon the different time and space scales one is investigating. The Colorado River has notable changes in reach-scale gradient along its entire length, and researchers are investigating this issue at both small and large scales, from how debris fans, pools, and rapids control the channel morphology and bed grain size, and thus the detailed profile of the modern, mixed alluvial-bedrock stream (e.g., Grams and Schmidt, 1999; Webb et al., 1989; Howard and Dolan, 1981), to how bedrock strength, tectonic knickzones, and the long-term history of drainage capture may influence the larger reach-to-canyon-scale profile. The issue becomes more complicated with the evidence that the Colorado River has undergone high amplitude cycles of aggradation-degradation in response to climate changes, as is evident in its sequence of thick Pleistocene fill terraces (Anders, 2003; Lucchitta et al., 2000; Machette and Rosholt, 1991). But the net product of this changing river has been overall bedrock incision, and for significant episodes the river has been a bedrock stream cutting the Grand Canyon, potentially sensitive to other controls on gradient such as bedrock properties.

In summary, it is unclear what is controlling the larger-scale profile of the river, and to what degree the controls on the local gradient of the modern river (debris fans, etc.) are superimposed upon and reflect larger-scale, longer-term controls (cf. Howard et al., 1994). One thing that is clear is that the localized aggradation Hanks and Blair infer, if happening, is at most a Holocene phenomenon superimposed on the longer-term trend of incision. In any case, if we add the upper estimate Hanks and Blair provide of 30 m of alluvium beneath the deeper pools of the river, the eastern Grand Canyon bedrock incision rate would be ~230 m/m.y. instead of our ~150 m/m.y. This somewhat greater rate would not invalidate our interpretations, but only amplify the fact that the Colorado River has actively and variably incised the Grand Canyon over middle–late Quaternary time.

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