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Effects of tributary debris on the longitudinal profile of the Colorado River in Grand Canyon

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[1] The Colorado River in Grand Canyon has long been known as a ''rapids-and-pools'' river, with the rapids owing their existence primarily to tributary debris flows. The debris flows deposit subaerial debris fans that constrict the channel laterally and, when they enter the river, raise the bed elevation. The rapids are short-wavelength ($\sim$0.1 to $\sim$1 km), small-amplitude ($\leq \sim$5 m) convexities in the river's longitudinal profile, arising from the shallow gradient in the upstream pool and the steep gradient through the rapid itself. Analysis of the entire longitudinal profile through Grand Canyon reveals two long-wavelength ($\sim$100 km), large-amplitude (15–30 m) river profile convexities: the eastern canyon convexity between river mile (RM) 30 and RM 80 and the western canyon convexity between RM 150 and RM 250. Convexities of intermediate scale are also identified in the longitudinal profile. These longer-wavelength, larger-amplitude convexities have strong spatial correlations with high rates of debris flow occurrence, high densities of Holocene debris fans, the largest debris fans along the river, and alluvial thicknesses of 10 m or more. River profile convexities are unstable and require an active and powerful geologic process to maintain them, in this case the abundant, frequent, and voluminous Holocene debris flow activity in Grand Canyon. At all wavelengths the most likely cause for these river profile convexities is Holocene aggradation of the riverbed beneath them, driven by the coarse particles of tributary debris flows. Large enough debris flows will slow river flow for kilometers upstream, causing it to drop much of its suspended load. Integrated over time and all of the tributary point source contributions, this process will build short-wavelength convexities into long-wavelength convexities. For most if not all of the Holocene the Colorado River has been dissipating most of its energy in the rapids and expending the remainder in transporting fine sediment through Grand Canyon, with little or no regional incision of bedrock.

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1. Introduction

[2] The principal concern of this paper is the longitudinal profile of the Colorado River in Grand Canyon and the profile convexities that are expressed along it across a wide range of wavelengths, from $\leq$1 km to $\geq$100 km. At short wavelengths, these convexities are associated with individual rapids and are defined by the flattened gradient of the upstream pool and the steepened gradient through the rapid itself. It has long been recognized that the rapids in Grand Canyon are created by tributary debris flows, which constrict the river laterally and raise its bed vertically [*Howard and Dolan*, 1981; *Kieffer*, 1985; *Webb et al.*, 1989; *Howard et al.*, 1994]. We show here that these river profile convexities at all wavelengths have a strong spatial association with the abundant, frequent, and voluminous debris flow activity in Grand Canyon [*Webb et al.*, 1989, 2003] that has persisted throughout the Holocene [*Hereford et al.*, 1996, 1998]. Less obvious is whether the short-wavelength convexities are causally related to the long-wavelength features and, if so, the mechanism by which short-wavelength convexities aggregate into the longer-wavelength ones.

[3] The observations and arguments we develop in this study exist within the context of the important place that longitudinal profiles have held in fluvial geomorphology since the writings of G. K. Gilbert more than a century ago [e.g., *Gilbert*, 1880]. It has long been known, especially in the case of ''graded'' or ''equilibrium'' systems [*Mackin*, 1948] that the longitudinal profiles of rivers both great and small are generally concave up; long ago, *Mackin* [1948] presented the conditions for which this should be the case (and why it often is not), a field of research that remains vigorous to the present day [*Howard*, 1998; *Rice and Church*, 2001; *Stock et al.*, 2005].

[4] If the general condition of the graded or equilibrium river is a concave-up profile, the Colorado River traversing

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the Colorado Plateau is decidedly not "graded" or not in "equilibrium," exhibiting both major and minor convexities at many scales in its longitudinal profile. As loosely defined here, a river profile convexity is determined by a relatively flat river gradient on its upstream limb and a relatively steep gradient on its downstream limb. Such gradient conditions, however, can result from soft, less erosion-resistant rock forming the river's bed (flatter gradients) upstream from harder, more erosion-resistant rock (steeper gradients) downstream. An interesting counterpoint to this common association is that the steepest reach-averaged gradient of the Colorado River on the Colorado Plateau is through Cataract Canyon, just downstream from the confluence of the Green River and the Colorado in Utah. This reach of the river forms the falling limb of the Cataract convexity and is entirely underlain by alluvial fill up to 80 m thick [*Webb et al.*, 2004]. River profile convexities are also the geometrical consequences of knickpoints, stationary or not, which might arise from a local or regional downstream base level fall and/or tectonic activity. It is not our point that the various circumstances above do not make for river profile convexities; it is our point that tributary debris flows are yet another mechanism for doing so.

[5] Quantitative analyses of river dynamics [e.g., *Howard et al.*, 1994; *Hancock et al.*, 1998; *Whipple et al.*, 2000; *Hancock and Anderson*, 2002] generally avoid dealing with transient aggradation of river beds due to episodic debris flow activity, in part because of the large particles involved, with dimensions that can be a significant fraction of the river channel dimensions, but also because so little is known about debris flow activity for most rivers. Indeed, the only reason our study is possible at all is the remarkable data set available for debris flow activity in tributaries of the Colorado River in Grand Canyon that we put in play below, a body of data that neither in quality nor in quantity exists for any other river.

[6] Even so, the significance of these matters has not gone unrecognized. *Pratt et al.* [2002] proposed a remarkable episode of Holocene aggradation and subsequent incision for the Marsyandi River in the Nepal Himalaya, both for the amount of alluvial fill and the brevity of its emplacement, to satisfy cosmogenic abundance data for fluvially cut bedrock exposed on the canyon walls. At least 80 m of hillslope-derived alluvium filled the Marsyandi gorge at $\sim$7 ka, thought to be driven by enhanced monsoonal precipitation, and was excavated in fairly short order. Even within rugged mountains, then, bedrock incision is likely to be discontinuous due to transient aggradation of the river channel driven by climatic pulses. *Korup* [2006] has recently demonstrated the effects of Holocene rockslides on the longitudinal profiles of rivers in New Zealand and Switzerland. The positions of these rockslides are correlated with significant perturbations in the steepness index, which in turn are commonly associated with river profile convexities.

[7] This study also should be viewed in the context of the long history of thinking about the origin and evolution of the Colorado River, especially in its Grand Canyon reach. While early scientific thinking held that the Colorado River drainage system was of great antiquity, dating from the waning stages of the Laramide Revolution in the early Tertiary, recent work has shown that the lower Colorado River, including most if not all of its Grand Canyon reach, is relatively young, $\leq$5 to 6 Ma [*Lucchitta*, 1990].

[8] That the Colorado River has incised as much as 2 km of Paleozoic and pre-Cambrian rocks in its Grand Canyon reach in just $\sim$5 My is an awesome rate of incision, even as an average rate of 400 m/My. Not surprisingly, then, the Colorado River is considered by most observers to be a bedrock river continuously incising bedrock. Equally if not more awesome, however, is the volume of rock excavated from tributary canyons in Grand Canyon over the same time interval and delivered to the river as very coarse sediment by rockfalls, landslides, and debris flows. This volume of rock is one to two orders of magnitude greater than that of the river corridor slot, $\sim$100 m wide, excavated by the river. This coarse sediment, delivered to the river over the past 5 My, is then available to cover the river bottom for unknown but perhaps significant amounts of time. It is known from both field [*Howard*, 1998] and laboratory [*Sklar and Dietrich*, 1998, 2001] observations as well as from numerical simulations [*Hancock and Anderson*, 2002] that even modest amounts of alluvial cover inhibit erosion/incision of the bedrock beneath it.

[9] By dint of this volume ratio alone, it would seem that the Colorado River in Grand Canyon is unlikely to be a bedrock river continuously incising bedrock but rather a river that is repeatedly subjected to transient episodes of aggradation and incision, probably driven by climatic fluctuations. We explore this possibility in this paper by examining the most recent (Holocene) episode of aggradation and its effects on the longitudinal profile of the Colorado River in Grand Canyon. We assemble available data for Holocene debris flow rates, debris fan areas and locations, and thicknesses of alluvium along the river corridor to show that they all have a strong spatial association with the locations of the river profile convexities at all wavelengths. We conclude that the river profile convexities are primarily due to Holocene aggradation of the riverbed beneath them.

[10] Our data, results, and conclusions are much the same as those of *Grams and Schmidt* [1999] for the Green River in Dinosaur National Park, in the Colorado River drainage far upstream from Grand Canyon. They showed that the tributary debris fans were primarily located in the three reaches of the Green River in Dinosaur expressing river profile convexities, although they did not associate any significance to these convexities. Also as in Grand Canyon, drill holes at three sites in Dinosaur revealed 12 to 45 m of alluvial fill. Finally, *Grams and Schmidt* [1999] concluded that for the Green River in Dinosaur National Park "the channel has been dominated by aggradation in recent geological time." This is the same conclusion we reach here for the Colorado River in Grand Canyon, with the additional specification that "recent geological time" is the Holocene.

2. Geologic and Geomorphic Characteristics of the Colorado River in Grand Canyon

[11] The river profile convexities that we present in the following section have strong spatial associations with the geomorphic reaches defined for the Colorado River in Grand Canyon [*Melis*, 1997], the spatial and temporal rates

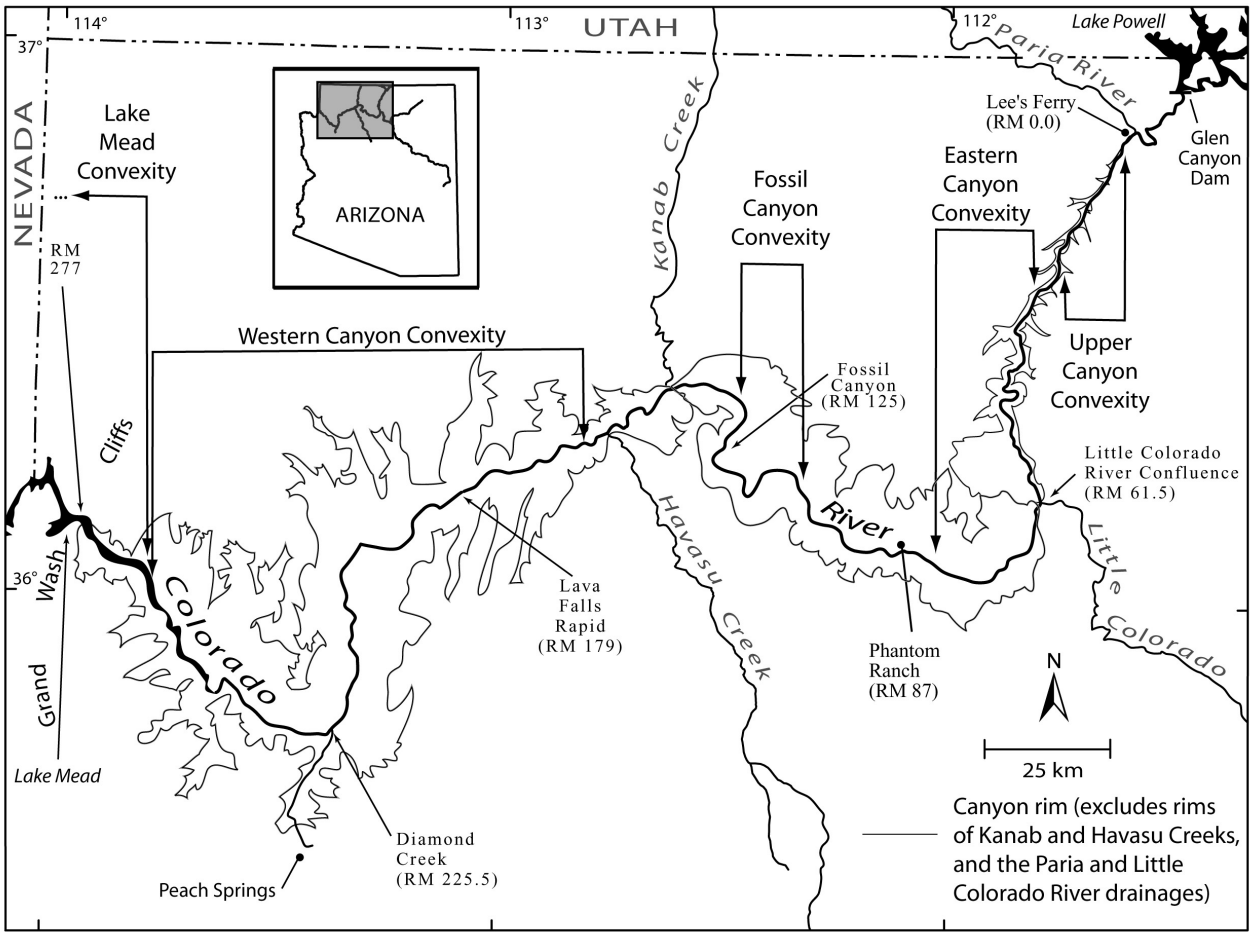

Figure 1. Map of the Colorado River through Grand Canyon showing the spatial extent of longitudinal profile convexities described in the text.

of tributary debris flow activity [*Griffiths et al.*, 2004], and the available (but still sparse) data on alluvial fill in the canyon bottom. We briefly describe these attributes here and associate them with specific river profile convexities in the next section.

[12] Figure 1 shows the Colorado River in its Grand Canyon reach. The general term "Grand Canyon" refers to all 277 miles (444 km) of canyon through which the Colorado River flows between Lee's Ferry and the Grand Wash Cliffs (Figure 1). For continuity with traditional practices and established reference points, we locate tributary confluences and other features by river mile [*Stevens*, 1983] but refer to intervening distances and elevations in metric units. Lee's Ferry is at river mile (RM) 0.0, Diamond Creek at RM 225.5, and the Grand Wash Cliffs at RM 277 (Figure 1).

2.1. Geomorphic Reaches

[13] Both the concepts and specific attributes of the geomorphic reaches of the Colorado River in Grand Canyon have evolved over the past two decades, from the original definitions of *Howard and Dolan* [1981], through the analysis of *Schmidt and Graf* [1990], to the most recent classification of *Melis* [1997], summarized here in Table 1 and displayed in Figure 2. Geomorphic reaches (GR) are defined by physical, geological, and hydrological characteristics of the river itself and the canyon it flows through, the most important of which are (1) the width of the river channel, which may or may not equal the width of the river corridor, as defined by the distance between the base of the talus slopes on opposing sides of the river, (2) the character and width of bedrock at or near river level, especially its potential for slope failure and debris flow initiation and mobilization, and (3) the size and location of tributary debris flow fans, which together with their associated fan-eddy complexes are important reservoirs of sediment storage through the Grand Canyon. In the Grand Canyon, the principal sources of debris flows that reach the river are the failure-prone Hermit Formation, the upper members of the Supai Group, and the Bright Angel Shale–Muav Limestone sequence [*Griffiths et al.*, 2004].

[14] Of the nine geomorphic reaches or subreaches summarized in Table 1, GR 3 and 5 have the widest channel and river corridor. Both of these reaches have either Muav Limestone, Bright Angel Shale, or Tapeats Sandstone at river level; in addition, GR 3 has members of the Proterozoic Grand Canyon Supergroup at river level. Although each of these formations has resistant layers, most of their thicknesses are composed of relatively erodible sedimentary rock, and these reaches have the second and third highest

Table 1. Geomorphic Reaches of the Colorado River in Grand Canyon[a]

Geomorphic Reach	Beginning River Mile (RM)	Ending River Mile (RM)	Average Channel Width, m	Average Density of Debris Fans, number RM^{-1}	Geology at River Level[b]
1	0	8	108	1.1	KL, CS, HF
2	8	38	83	1.8	SG, RL, ML
3	38	77	133	2.6	ML, BAS, TS, GCSG
4	77	170	69	1.2	ML, BAS, TS, VS, A, ZG
4A	87	100	84	0.9	VS, A, ZG
4B	116	128	93	3.1	BAS, TS, A, ZG
5	170	213	126	2.2	ML, BAS, TS
6	213	262[c]	103[c]	1.9[d]	VS, ZG
7	262	277	–	–	ML, BAS, TS

[a]Modified from *Melis* [1997, Table 5.3].
[b]KL, Kaibab Limestone; CS, Coconino Sandstone; HF, Hermit Formation; SG, Supai Group; RL, Redwall Limestone; ML, Muav Limestone; BAS, Bright Angel Shale; TS, Tapeats Sandstone; GCSG, Grand Canyon Supergroup; VS, Vishnu Schist; A, amphibolite; ZG, Zoroaster Granite.
[c]According to *Melis* [1997], geomorphic reach (GR) 6 ends at RM 225, the downstream limit of his field research. In this study, we have extended GR 6 to RM 262, where Paleozoic rocks again crop out at river level and the Lower Granite Gorge ends. We define GR 7 to extend from this point to Grand Wash Cliffs.
[d]Channel width and debris fan data end at RM 225.5.

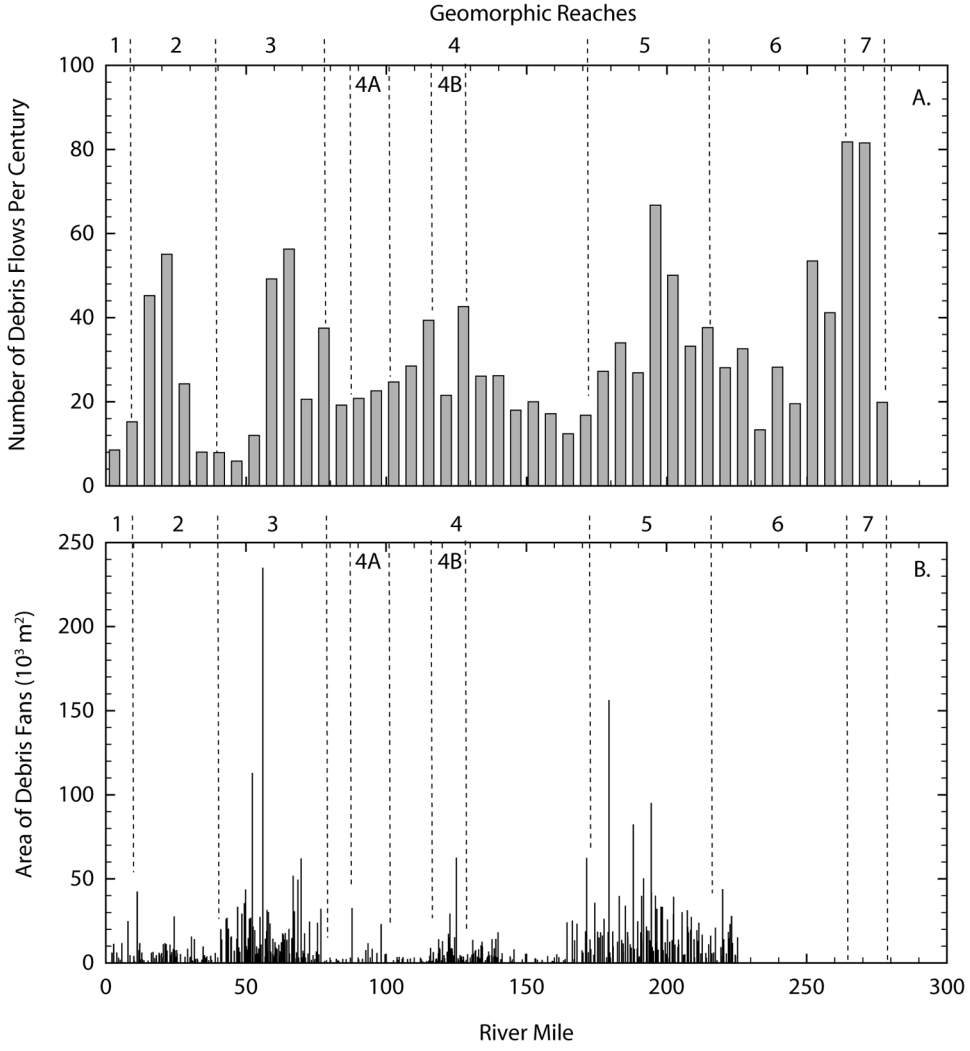

Figure 2. (a) Frequency factors of debris flows summed in 10 km increments along the river corridor (modified from *Webb et al.* [2000]). (b) Locations and areas (in units of 10^3 m^2) of 444 Holocene tributary debris flow fans between Lee's Ferry and Diamond Creek [*Melis*, 1997]. In both Figures 2a and 2b the geomorphic reaches of *Melis* [1997] are shown as vertical dashed lines and the numbers between them.

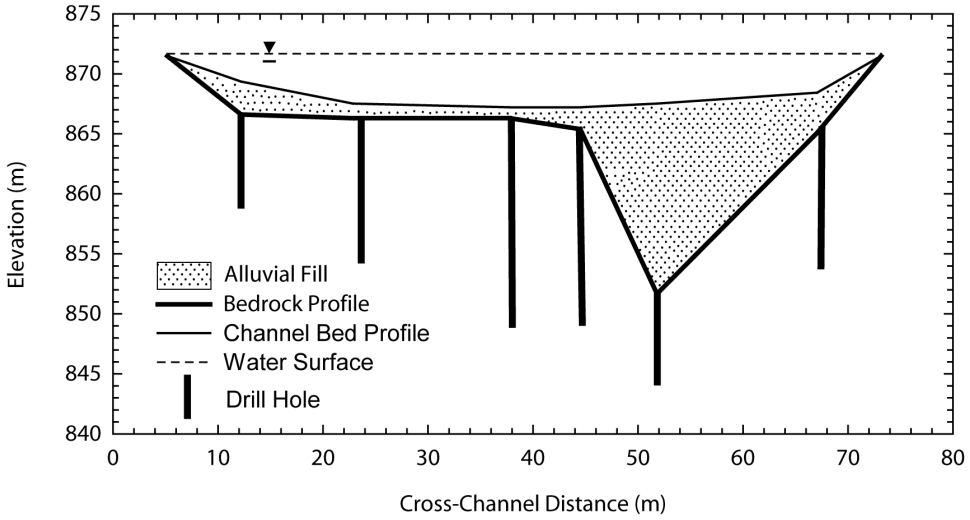

Figure 3. Cross section of the Colorado River at RM 32.9 showing alluvial fill, channel geometry, and depth to bedrock (Muav Limestone) as determined by the Bureau of Reclamation (unpublished data, 1950) using six drill holes.

density of debris fans of the nine reaches. GR 2 has Supai Group, Redwall Limestone, and Muav Limestone at river level and has a narrow channel width (Table 1). In contrast, geomorphic reaches 4 and 6 mostly have Vishnu Schist or Zoroaster Granite at river level; these likely are the most resistant rock units in Grand Canyon. GR 4, which includes Upper Granite Gorge (RM 77–108) and Middle Granite Gorge (RM 126–130), has the narrowest channel width. GR 4 has sufficient lithologic diversity, however, to warrant subreaches 4A and 4B [*Melis*, 1997]. GR 4B, in particular, is of intermediate channel width and has the highest density of debris fans in Grand Canyon. GR 6 is defined by the Lower Granite Gorge (RM 213–262), the lower half now being beneath Lake Mead. GR 7, which does not concern us here, is entirely inundated by Lake Mead.

[15] There is a well-known correlation between locations of the largest debris fans and wide, open reaches of the river corridor, which mostly occur in GR 3 and 5 (Figure 2b). Less obvious, however, is whether this points to a causal (physical) connection or whether this is simply geometrical common sense: large debris fans occur only where the river corridor can accommodate them, namely where it is wide and open.

[16] A more likely physical cause of a wide, open river corridor is bedrock with a propensity for slope failure and debris flow initiation and mobilization at or near river level. This occurs in GR 3 and 5 with the Bright Angel Shale and in GR 3 with certain clay-rich members of the Grand Canyon Supergroup [*Griffiths et al.*, 2004]. Tributary drainages in these wide, open corridors tend to be longer with greater catchment areas, with correspondingly greater potential for large debris flows and fans. In this view, all of the three principal characteristics of geomorphic reaches are related to each other, and together they strongly suggest that GR 3 and 5 should be the loci of unusual quantities of tributary debris delivered to the fans adjacent to the river and into the river itself. This is indeed the case.

2.2. Debris Flow Activity

[17] Debris flows occur commonly in 740 tributaries of the Colorado River in Grand Canyon, and stratigraphic analyses indicate that debris flows have occurred throughout the Holocene [*Melis et al.*, 1994; *Lucchitta et al.*, 1995; *Hereford*, 1996; *Hereford et al.*, 1996, 1998]. *Webb et al.* [2000] and *Griffiths et al.* [2004] present empirical data and statistical analyses of debris flow frequency in Grand Canyon. Using the approach of *Haan* [1977] and the logistic probabilities of *Griffiths et al.* [2004], we updated the debris flow frequency factors for Grand Canyon as originally presented by *Webb et al.* [2000]. We present them here as the number of debris flows per century, averaged over 10 km reaches through Grand Canyon (Figure 2a). Figure 2b shows locations and areas of the 444 Holocene debris fans between Lee's Ferry and Diamond Creek, where the data set of *Melis* [1997] ends.

[18] GR 3 and 5 are the loci of both high rates of debris flow activity as well as large debris fan areas and densities, as anticipated above. GR 2 has relatively high rates of debris flow activity, at least in its upper reaches where the failure-prone Hermit Formation is near river level, but has small debris fan sizes because the canyon is narrow in this reach. The longest geomorphic reach (150 km) is GR 4 through the Upper and Middle Granite Gorges; the short GR 4B, where the geology at river level returns to the basal Paleozoic and the weak Bright Angel Shale, has higher debris flow activity and debris fan sizes and densities.

2.3. Depth to Bedrock and Thickness of Alluvium

[19] Although it is generally assumed that the Colorado River mostly flows on bedrock, considerable evidence suggests that the alluvial fill in the canyon bottom has significant thickness, both beneath the river and along its margins. From 1943 through the late 1950s, the Bureau of Reclamation drilled test holes into the riverbed at potential dam sites (Figure 3 and Table 2). These sites include the place where Glen Canyon Dam now stands (RM -15.5 and (D. Grundvig, Bureau of Reclamation, written communication, 2003)), the upper and lower Marble Canyon dam sites (between RM 32.8 and 39.5 (J. J. Hammond and R. Rhoades, Bureau of Reclamation, written communication, 1950, 1952)), and the Gneiss and Separation Canyon

Table 2. Measurements of Depth to Bedrock Beneath the Colorado River in Glen, Marble, and Grand Canyons

RM	Maximum Depth to Bedrock, m	Data Source[a]	Date of Data Collection	Type of Data	Reliability
−15.5	16.8	reclamation	1956	drill holes	high
32.8	20.4	reclamation	1950	drill holes	high
39.5	27.4	reclamation	1952	drill holes	high
47.0	44.8	Rubin	1990	seismic	high
51.5	>13.4	Rubin	1991	seismic	high
52.0	>17.1	Rubin	1991	seismic	high
53.0	>25.9	Rubin	1991	seismic	high
65.5	9.4	Rubin	1990	seismic	high
119.1	15.9	Rubin	1990	seismic	high
122.2	10.2	Rubin	1990	seismic	high
168.0	1.8[b]	Rubin	1991	seismic	low
236.3	15.2	reclamation	1943	drill holes	high
237.5	13.7	reclamation	1943	drill holes	high
239.2	27.4	reclamation	1943	drill holes	high
240.0	15.2	reclamation	1943	drill holes	high

[a]Reclamation, Bureau of Reclamation (unpublished data, 1942, 1950); Rubin, D. M. Rubin (U.S. Geological Survey, unpublished data, 2003). The year in parentheses is when the measurement was made.

[b]We do not show the measurement of 1.8 m at Fern Glen Canyon (RM 168) in Figure 4 as this likely is a bedrock strath terrace underlying a sandbar.

dam sites (RM 237–239 (J. J. Hammond and R. Rhoades, Bureau of Reclamation, written communication, 1943)). Although considerable data are available from the excavation of alluvium at Glen Canyon Dam, most of the data in Marble and Grand Canyons consist of a cross section with 4–6 drill holes that penetrated into the bedrock underlying the alluvial fill (Figure 3).

[20] Seismic data collected to characterize the geometry of sandbars [*Rubin et al.*, 1994] also reveal the depth of the alluvial fill (Table 2). These data are less useful than the drill hole data from cross sections because they were collected on channel margins that may not reflect the true depth to bedrock; however, the seismic data were collected at more sites and provide more longitudinal coverage than the drill hole data alone.

[21] Depth-to-bedrock data from RM 32 to 240 are shown in Figure 4a, together with the longitudinal profile of the Colorado River [*U.S. Geological Survey*, 1924]. While the bedrock profile is shown as a continuous line, it consists mostly of straight line segments connecting successive points of maximum depths of alluvial fill (Table 2). As some abrupt changes in bedrock gradient suggest (at RM 50; for example, Figure 4), more data are required before a realistic bedrock gradient can be developed for the Colorado River in Grand Canyon. Even so, Figure 3 suggests that the bedrock geometry can be complicated, even on the scale of the river/canyon widths. Similarly, the fine detail in Figure 4b, the difference between the two profiles in Figure 4a and nominally the alluvial fill thickness, is due almost entirely to the detail in the river profile, detail mostly lacking in the bedrock profile. Nevertheless, Figures 3 and 4 and Table 2 all suggest that significant amounts of alluvial fill exist in the canyon bottom, with the exceptions of the Upper, Middle, and Lower Granite Gorges.

[22] From these attributes, we conclude that (1) there are considerable volumes of alluvial fill in the canyon bottom, both in the channel and along the river corridor adjacent to it, (2) the greatest thicknesses of this alluvium generally occur in regions of high debris flow activity, and (3) the regions of high spatial and temporal debris flow activity tend to occur in those geomorphic reaches with a high propensity for slope failure. As we shall see in section 3, the river profile convexities at all wavelengths share these same spatial affinities, which will lead us to conclude that they are fundamentally due to alluvial fill in the river channel caused by the combined effects of deposition from tributary debris flows and main stem sediment load dropped into still water ponds upstream of the tributary debris flows and fans.

3. Colorado River Profile Convexities

[23] Figure 5 illustrates how we identify the river profile convexities from Lee's Ferry to Grand Wash Cliffs using the 1923 profile [*U.S. Geological Survey*, 1924]. According to *Leopold* [1969], the steep, average gradient (long-dashed line) "shows that the river profile, although slightly irregular, is nearly straight." The most obvious of these "irregularities" are the convex-up portions of the river profile between RM ~30 and ~80 and RM ~150 and ~250. These are the eastern canyon convexity and the western canyon convexity of *Hanks and Blair* [2003].

[24] Figure 5c shows the detrended river profile, the difference between the actual river profile and its average gradient of 0.0015 defined by the RM 0 and RM 277 endpoints. There is nothing physically significant about this average gradient; it is just the most transparent way of detrending the profile, allowing us to see much smaller-scale features, down to the scale of individual rapids, as well as to estimate their amplitudes. While this average gradient of 0.0015 is unlikely to be uncertain by more than ±0.0001, which translates to ±44 m of elevation at one endpoint or the other, it provides little constraint on average gradients on more local scales. Also shown in Figure 5 are the geomorphic reaches of *Melis* [1997], which provide reference points to the debris flow and sediment thickness data shown in Figures 2 and 4, respectively.

[25] The Eastern Canyon convexity stands ~25 m above the average river gradient, and Figure 4b suggests as much as ~40 m of alluvial fill underlies it. The western canyon convexity, of somewhat greater wavelength, has a comparable thickness of alluvial fill beneath it. Also discernible in Figure 5c, at shorter wavelengths, are the uppermost canyon convexity (RM 3 to 25) and the Fossil Canyon convexity (RM 112 to 130). No depth-to-bedrock data are available for the reach of uppermost canyon convexity, but the Fossil Canyon convexity is readily apparent in Figure 4b. Three additional, short-wavelength convexities ride on the rising limb of the western canyon convexity and are associated with individual rapids, Lava Falls (RM 179) being the most obvious (Figure 5c). The ten largest rapids as measured by elevation drop (Table 3) are also identified in Figure 5c.

3.1. Long-Wavelength Convexities (~100 km)

[26] The eastern canyon convexity (ECC) is easily discernible in Figures 5a and 5c and extends at least from RM ~30 to ~80. It stands as much as 25 m above the average river gradient and even higher at Nankoweap (RM 52) and Kwagunt Rapids (RM 56). ECC, from RM ~40 to ~80, is also apparent in Figure 4b. ECC occupies all of GR 3,

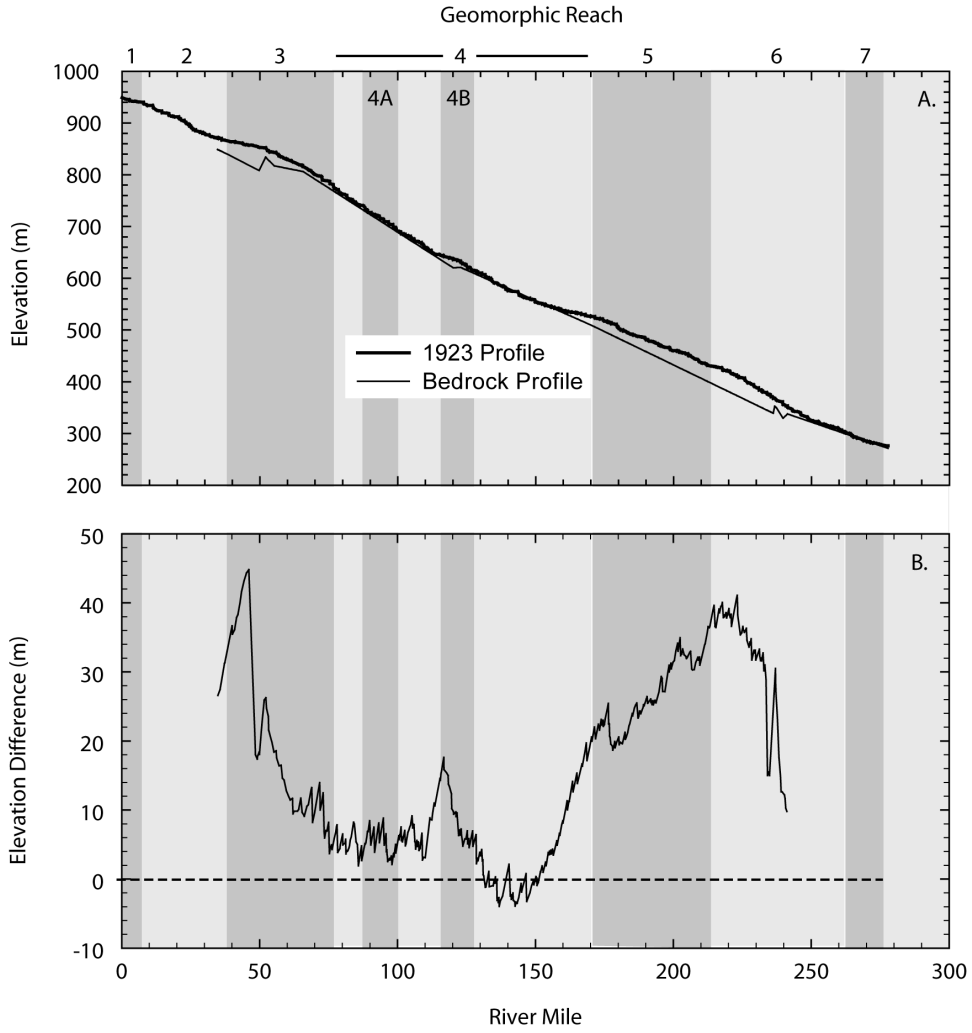

Figure 4. (a) Longitudinal profile of the Colorado River through Grand Canyon (thick trace) and depth-to-bedrock profile (thin line segments) constructed by connecting the data points in Table 2 with straight line segments. (b) Alluvial thickness profile, the difference between the two profiles in Figure 4a.

perhaps extending ~10 km both above and below it and is plainly associated with a large number of tributary fans; 7 of the 14 largest debris fans in Grand Canyon are also in this reach [*Webb et al.*, 1999a, Table 5]. The falling limb of ECC, beginning at RM ~70 and the Upper Granite Gorge (Figure 5c), is also clearly associated with falling debris flow activity rates (Figure 2a), decreasing debris fan area and densities (Figure 2b), and decreasing alluvial thickness (Figure 4b).

[27] ECC initiates where the river corridor begins to widen from its upstream aspect even before the fine-grained, easily erodible Bright Angel Shale first appears at river level at RM 49. For the next ~50 km, the river corridor widens considerably more as it and its tributaries traverse this unit and the likewise easily erodible formations of the mid to late Proterozoic Grand Canyon Supergroup. Abundant, fine-grained, clay-rich, erosional detritus of the sort available from RM 49 to 77 is known to be an important ingredient for mobilization of debris flows in the Grand Canyon [*Webb et al.*, 2000, 2003].

[28] Sparse data on fill thickness have been collected in this reach. At RM 32.8, holes drilled at the Marble Canyon dam site revealed a depth to bedrock of 17–23 m (Figure 3); a second site, at RM 39.5, had a maximum fill depth of 27.4 m (Table 2). Seismic refraction lines along the beaches and sandbars between the canyon walls and river edge at Saddle Canyon (RM 47), Lava Canyon (RM 65.5), and at three sites above, at, and below Nankoweap Rapid (RM 52) in most cases show bedrock at significant depths ($\geq$10 m below river level) beneath debris fill consisting of sand, gravel, boulders, and talus (Table 2). At RM 77, the canyon narrows where the Vishnu Schist and Zoroaster Granite are first exposed, at the top of Upper Granite Gorge. ECC, however, extends some distance into Upper Granite Gorge, perhaps as much as 15 km.

[29] The western canyon convexity (WCC) is also easily discernible in Figures 4a, 4b, 5a, and 5c, extending from RM ~150 to 250. WCC begins just before GR 5, where the Bright Angel Shale again crops out at river level. WCC encompasses all of this reach and most of GR 6, extending well into Lower Granite Gorge. Like ECC, WCC is associated with both a large number of tributary fans and 6 of the 14 largest debris fans [*Webb et al.*, 1999a, Table 5]. The falling limb of WCC, beginning at Diamond Creek (RM

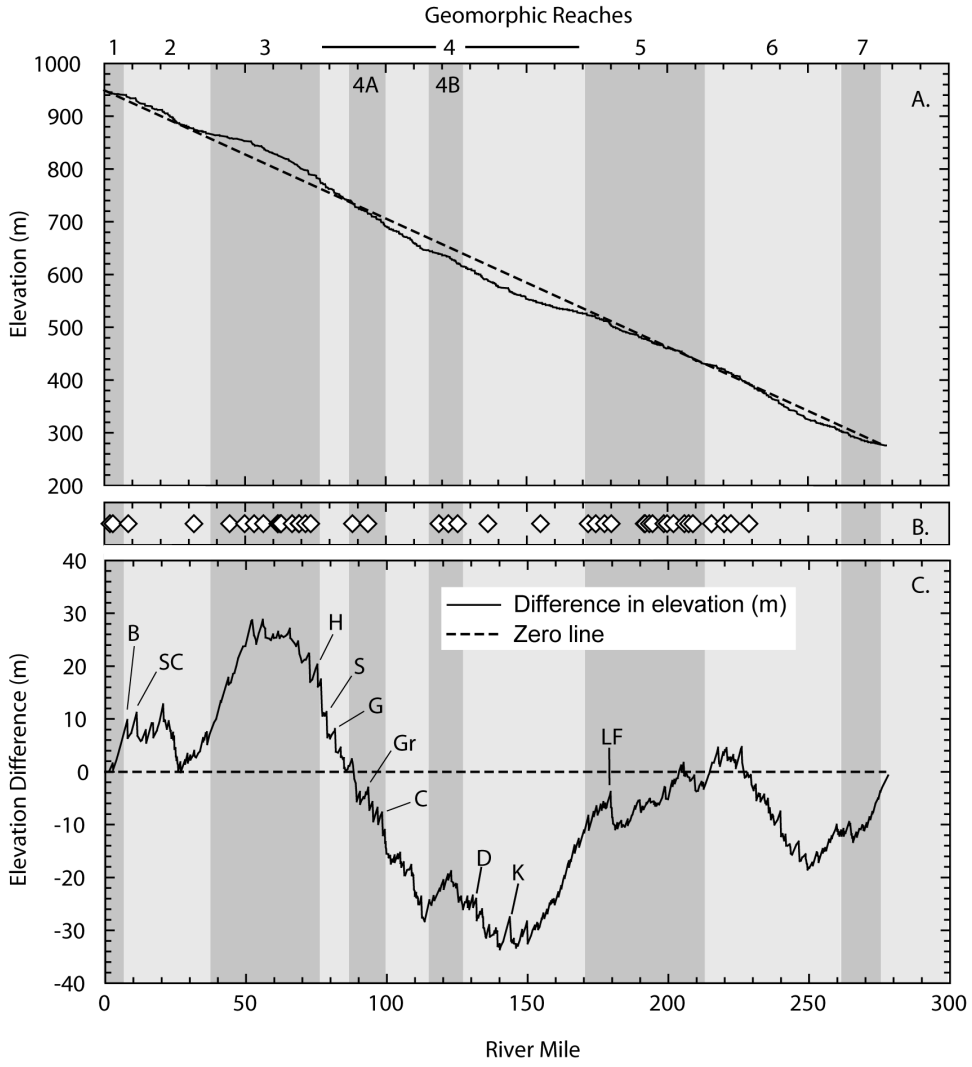

Figure 5. (a) Longitudinal profile of the Colorado River in Grand Canyon (thick trace) and the average gradient of 0.0015 between Lee's Ferry and Grand Wash Cliffs (dashed line). Geomorphic reaches of *Melis* [1997] are indicated by the alternating shaded patterns and the numbers at the top. (b) Locations of alluvial islands in the Colorado River in Grand Canyon, from *Stevens* [1983]. (c) Difference between the two profiles in Figure 5a, showing the principal river profile convexities. From upstream (left) to downstream (right) the rapids identified in Figure 5c are Badger Creek (B), Soap Creek (SC), Hance and Lower Hance (H), Sockdolager (S), Grapevine (G), Granite (Gr), Crystal and Lower Crystal (LC), Dubendorff (D), Kanab (K), and Lava Falls and Lower Lava (LF) rapids.

225, Figure 5b), is, like the falling limb of ECC, also associated with falling debris flow activity rates (Figure 2a), decreasing debris fan area and densities (Figure 2b), and decreasing alluvial fill thickness (Figure 4b).

[30] Except for the part in Lower Granite Gorge, WCC occupies a river corridor that is again relatively wide. Unlike ECC, however, WCC is associated with active tectonics and volcanism, as well as with the active debris flow deposition shared with ECC. From east to west, the Mohawk–Stairway (RM 171.5), Toroweap (RM 179), and Hurricane faults (RM 188), all northerly trending, down to the west, active normal faults, traverse WCC. Each of these fault-controlled valleys contains large debris flow fans.

[31] The most remarkable of these is Prospect Canyon (RM 179.4), a Toroweap fault- controlled structure sensational for the intensity and variety of active geologic processes in play in this theater, including faulting, volcanism, erosion, a 300 m waterfall, debris flows, and river dynamics at Lava Falls, the largest of the Grand Canyon rapids. The geologic and topographic setting of Prospect Canyon make for frequent debris flows [*Webb et al.*, 1999a], which create and maintain Lava Falls Rapid. Photographic documentation of these debris flows during the 20th century includes a dramatic 300 m waterfall (the "fire hose") of Prospect Creek into Prospect Canyon [*Webb et al.*, 1999a, Figure 27], responsible for the debris flow of March 1995.

[32] The Toroweap fault also bounds the Uinkaret volcanic field on its eastern margin and, just north of the river, bisects Vulcan's Throne, the source of voluminous, half million years old basaltic lava [*Lucchitta et al.*, 2000; *Pederson et al.*, 2002] that flowed down the Colorado River

Table 3. The 10 Rapids With the Largest Drops in Grand Canyon[a]

Order	River Mile	Rapid Name	Drop in 2000, m
1	82.1	Grapevine	5.99
2	144.0	Kanab	5.55
3	79.1	Sockdolager	5.52
4	77.2	Hance	5.26[b]
5	11.4	Soap Creek	5.00
6	93.9	Granite	4.56
7	132.3	Dubendorff	4.42
8	8.0	Badger Creek	4.28
9	99.0	Lower Crystal	4.19[c]
10	179.7	Lava Falls	4.16[d]

[a]Adapted from *Webb et al.* [2000] and *Magirl et al.* [2005].
[b]If Hance Rapid and its first secondary rapid are combined without the intervening slower water, the total drop is 8.71 m.
[c]If Upper and Lower Crystal Rapids are combined, the total drop is 6.24 m.
[d]If Lava Falls and Lower Lava Rapids are combined, the total drop is 5.69 m.

to RM 240. Yet-to-be-eroded remnants of these lava flows in the river channel are a possible cause of WCC, but in the absence of access to the channel beneath the present river level, this mechanism is difficult to prove one way or the other. This possibility cannot, of course, be applicable to ECC.

[33] The Hurricane fault bounds the Uinkaret volcanic field on the west and is near the eastern margin of an intensely faulted domain that extends from the Hurricane fault system, itself with many splays and splinters in the vicinity of the river corridor, west to the Grand Wash Cliffs [*Huntoon and Billingsley*, 1981, 1982]. Erosion abetted by faulting is likely to be an important source of detritus to the river between Whitmore Wash (RM 188), where the fault departs the river corridor north to the Hurricane Cliffs, and Diamond Creek (RM 225), where the fault departs south toward Peach Springs, Arizona.

[34] The Lake Mead convexity is the third, long-wavelength, river profile convexity. It begins to build at RM ~250 (Figure 5c), coincident with a marked increase in debris flow activity (Figure 2a), and extends at least as far as Boulder Canyon [*Leopold*, 1969, Figure 97]. Because it is mostly beyond the Grand Canyon in a domain where a very different average gradient might hold and because it is entirely inundated by Lake Mead at the present time, we do not consider it further.

[35] In summary, ECC and WCC share common features in their widened river corridors and abundance of large debris flow fans. In the eastern canyon, these features seem mostly related to the (static) condition of widespread exposures of easily erodible rocks conducive to slope failure and debris flow mobilization. In the western canyon, an additional (dynamic) factor contributing to erosion, debris flow mobilization, and the river profile convexity is the presence of active normal faulting, which contributes to erosion through extensive fracturing of near-surface rocks and extreme topographic gradients.

[36] ECC and WCC also share a fascinating association with the placement of major rapids, the short-wavelength convexities, as well as the locations of alluvial islands. The three longest reaches of the Colorado River in Grand Canyon without a major rapid, taken to be $\geq$6 according to the ratings of *Stevens* [1983], are the 49 km reach from RM 25 (Cave Springs Rapid) to RM 56 (Kwagunt Rapid); the 48 km reach from RM 150 (Upset Rapid) to RM 180 (Lava Falls); and the 42 km reach from Lava Falls to RM 205 (Kolb Rapid). The first of these constitutes the rising limb of ECC; the second two form most of the rising limb of WCC.

[37] In a certain respect, this association is not unexpected; relatively speaking, the river is "running uphill" for long distances on the rising limbs of these two river profile convexities (Figure 5c), and an elevation decrease in the form of a major rapid would be counterproductive in these circumstances. The consequence of this line of thinking, however, is that Lava Falls is uniquely and monumentally "counterproductive," the only interruption in what otherwise would have been a 90 km stretch without a major rapid. This underscores the remarkable ability of Prospect Canyon, the locus of the most frequent debris flows in Grand Canyon [*Webb et al.*, 1999a], to deliver debris to the river. Just the opposite happens on the falling limbs of ECC and WCC, both loci of numerous major rapids, some now inundated by Lake Mead in the case of WCC.

[38] Alluvial islands (Figures 5b and 6) occur infrequently in the Colorado River in Grand Canyon and, to

Figure 6. View of the Colorado River on the crest of the Eastern Canyon river profile convexity, looking south across an alluvial island (RM 52.3) and debris bars indicative of a reach overloaded with coarse sediment. View is from the river right canyon wall just south of Nankoweap Creek.

our knowledge, have received little scientific attention. We define alluvial islands as a subset of the larger group of debris bars [*Howard and Dolan*, 1981; *Webb et al.*, 1989], differing in that they are detached from the shore and emergent at ~280 m^3/s discharge. Alluvial islands consist of Colorado River sand and gravels locally derived from debris fans or lava flows [*Fenton et al.*, 2002, Figures 3 and 5] with only occasional far-traveled particles. Spatially, alluvial islands are placed almost antithetically to the major rapids, that is, they mostly occur on the rising limbs or on the crests of the longer-wavelength convexities (Figure 5b). They are especially abundant on or near the crests of ECC and WCC, although two alluvial islands are on the rising limb of the Uppermost Canyon convexity and three more are on the Fossil Canyon convexity, both described in more detail below.

[39] Figure 6 is a view down the crest of ECC from a point near Nankoweap (RM 52) and suggests a river corridor choked with alluvium. The island in the foreground stands only ~2 m above the present river level, but this is indicative of a former riverbed (or at least some subaqueous depositional site) now above the present river level. Given the unconsolidated nature of the sand and gravels that make up these islands and their consequent inability to resist the erosive forces of major floods, these islands point to a very recent drop in river level, possibly the one proposed by *Davis et al.* [2000] ~700 years ago to account for incision of the farmlands of the ancestral Puebloans and their consequent abandonment.

3.2. Intermediate-Wavelength Convexities (~10 km)

[40] The uppermost canyon convexity (UCC) extends from RM 3 to 25. Of almost unobservable amplitude in Figure 5a, it is clearly defined by the detrended river profile in Figure 5c, with amplitude of almost 10 m above the average river gradient. UCC resides almost entirely in GR 2 for which the narrow canyon in most cases precludes large fan areas. In UCC, only one of these, the Soap Creek debris fan, is large and is ranked 15th by area by *Webb et al.* [1999a, Table 5]. In terms of debris fans per river kilometer, however, UCC is only about 25% less than ECC and 10% less than WCC. UCC is also associated with high debris flow rates for the Colorado River in Grand Canyon (Figure 2a). The falling limb of UCC is coincident with the "Roaring Twenties," a sequence of closely spaced rapids between RM 20 and 27.

[41] The Fossil Canyon convexity (FCC) extends from RM 112 to 130. Like UCC, it is barely observable in Figure 5a but is easily discernible in Figure 5c; Figure 4b suggests FCC is underlain by as much as 15–20 m of alluvium. It is essentially coincident with GR 4b of *Melis* [1997], which begins at the Monument Fold exposing the Tapeats Sandstone at river level and ends at the head of Middle Granite Gorge. GR 4b and FCC possesses the highest density of tributary fans in the Grand Canyon, 5 per km. The Fossil Canyon fan (RM 125) has the 7th largest area of Grand Canyon debris fans [*Webb et al.*, 1999a, Table 5]. FCC is associated with a significant increase in debris flow probabilities from those just upstream (Figure 2a). The seismic refraction data show bedrock 15.9 m beneath debris fill at RM 119 and 10.2 m at RM 122 (Table 2).

[42] The Superposition Convexities (SpC) refers to the set of three, ~20 km long convexities superimposed on the rising limb of long-wavelength WCC. The first of these (Figure 5c) is plainly associated with Lava Falls at RM 179 and has an amplitude of 5–6 m. The second is at RM 205, has a smaller amplitude, and is associated with locally high debris flow activity rates (Figure 2a). The third occurs between RM 214 and 230 with an amplitude of ~8 m. It includes the debris fan at 220-Mile Canyon, 13th largest by area [*Webb et al.*, 1999a, Table 5] and the debris fan at Diamond Creek, inside Lower Granite Gorge.

3.3. Short-Wavelength Convexities (~1 km)

[43] Rapids form short-wavelength convexities along the river and are related to larger-scale convexities as shown in Figure 5c. Nankoweap Rapid (RM 52), Kwagunt Rapid (RM 56), and Diamond Creek Rapid (RM 226), among many others, are also easily discernible in Figure 5c. Rapids are known to be unstable to reworking by the river [*Howard and Dolan*, 1981; *Kieffer*, 1985; *Webb et al.*, 1999a], dispersing debris, including large boulders, from the primary rapid into secondary rapids and riffles downstream.

[44] *Magirl et al.* [2005] documented changes in elevation for 86 named rapids from Lee's Ferry to Diamond Creek between 1923 and 2000, when Lidar data were collected on river corridor topography. More rapids aggraded than degraded by a margin of 39 to 16 for elevation changes $\geq \mid 0.3 \text{ m} \mid$, the threshold of significant elevation change. Moreover, elevation increases were consistently larger than elevation decreases. Although the changes documented by *Magirl et al.* [2005] might be presumed to be attributable to operations of Glen Canyon Dam, completed in 1963, lack of documentation of rapids at the beginning of dam operations precludes any quantitative determination of flow regulation contributions to aggradation of rapids.

[45] The river has not yet been so enervated, however, that degradation of rapids no longer occurs; indeed, boulders are still transported out of rapids during even modest floods [*Webb et al.*, 1999b; *Pizzuto et al.*, 1999]. Despite operations of Glen Canyon Dam, the rapids experiencing elevation increases and decreases retain a clear association with the presence and absence of tributary debris flows. Of the 20 rapids with the largest elevation increases, 15 of their related tributaries have experienced one or more debris flows since 1923; of the 10 rapids with the largest elevation decreases, only three of the related tributaries have had debris flows since 1923 [*Magirl et al.*, 2005; C. S. Magirl, unpublished data, 2005].

[46] Debris fill in the channel of the Colorado River at any wavelength has its origins in tributary debris flows and fans that feed and aggrade the rapids. Volumetrically, however, debris fill invested in the rapids, either individually or collectively, is inconsequential to that invested in the longer-wavelength convexities. Assuming a constant cross-sectional channel geometry, a poor but necessary assumption, the area under the curve of any convexity with respect to a chosen gradient datum is proportional to its volume of debris fill. Treating each of these convexities as a half cycle sine wave, $C \sin(\pi x/L)$ where L is the length of the convexity and C is its amplitude, the area of the convexity is $2CL/\pi$. The long-wavelength convexities ECC and WCC have both L and C values several times greater than those for the intermediate-wavelength convexities UCC, FCC,

and SpC and so have debris volumes greater by a factor of 10 or more. The individual rapids, with L values smaller by a factor of 100 and C values smaller by a factor of 5 to 10, have areas smaller than the long-wavelength convexities by a factor of 500 or more, a discrepancy not offset by the dozens of major rapids through Grand Canyon. Neither is it likely that changes in channel geometry are of the right magnitude and sign at just the right places to explain these differences when treated as volumes. These volumetric discrepancies point to a physical connection between the short- and long-wavelength convexities which we develop in the following section.

[47] The rapids play an important role in locally dissipating the kinetic energy of the river. Much of the elevation drop of ~670 m through Grand Canyon (Figure 5a) occurs in just a small fraction of the river length occupied by the rapids. Following *Leopold* [1969], *Magirl et al.* [2005] found that 66% of the river drop in Grand Canyon occurred in just 9% of its length. On a pool-to-pool basis, however, there is apparently little or no change in the RMS value of the velocity field of the river, despite the potential energy available from the elevation drop between the two pools. Most if not all of this potential energy must be dissipated in the intervening rapid as turbulence, viscous shearing, and particle entrainment as the river attempts to remove the obstruction of the rapid.

4. Discussion and Conclusions

[48] While a number of observations and associations have been made in this paper from which several conclusions can be drawn, the most significant is that the longitudinal profile of the Colorado River in Grand Canyon has been altered by the accumulation of tributary debris in the river channel. In the case of the short-wavelength convexities, the responsible process is directly observable: most of the rapids occur where the channel is filled essentially to river level with debris, the origin of which is local tributaries. We also know from direct observations that these rapids are episodically replenished by debris flows; those that are not degrade, on timescales of decades to a century or so, even in the presence of regulated flow.

[49] The mechanism that connects the short-wavelength convexities to the longer-wavelength ones is, we believe, the aggregate behavior of all the point source contributions and the rapids they form in any long-wavelength convexity. In particular, large debris flows obstruct the river for some distance upstream, forming a low-velocity pool that accumulates much of the total sediment load of the river until the obstruction is breached. At an average river gradient of 0.0015, a debris fan just 1.5 m above the local water surface will slow flow a minimum of 1 km upstream without an intervening debris fan. On the rising limbs of ECC and WCC, however, the average river gradients are ~0.0005, and the length of the corresponding pool will be three times greater. Conversely, on the falling limbs of ECC and WCC, the average river gradients are more like 0.0025. As we have noted earlier, debris flow activity in Prospect Canyon creates the imposing Lava Falls Rapid, but it also seems responsible for lessening the river gradient ~30 km upstream (Figure 5c).

[50] Debris fans that greatly constrict the river will not long persist, perhaps not longer than the next flood in the predam river. Such damming and ponding can occur, however, at many locations along the river where large Holocene debris flows occur, but, as we have seen, these are preferentially in the long-wavelength convexities. This mechanism of building long-wavelength convexities from numerous short-wavelength convexities within them may also explain the volume discrepancies noted earlier, with the short-wavelength convexities having an aggregate volume of ~1% of the long-wavelength convexities. The short-wavelength convexities that control the rapids are built entirely from coarse tributary debris, while the longer-wavelength convexities owe their existence primarily to the coarse sand and fine gravels deposited in low-velocity pools. It perhaps is coincidence, but this volume ratio of ~1% estimated here is the same (within considerable uncertainty) as the ratio of mass delivered annually by tributary debris flows ($0.14–0.30 \times 10^6$ Mg/yr [*Webb et al.*, 2005]) to the mass of the annual sediment load carried by the predam Colorado River ($\sim 25 \times 10^6$ Mg/yr [*Wright et al.*, 2005]).

[51] The close spatial associations of the longer-wavelength convexities with the locations and sizes of debris fans, the frequency of debris flows, alluvial thicknesses of >10 m, and the occurrence of alluvial islands lead us to conclude that unusual accumulations of alluvial fill in the channel are their principal cause, just as debris flows are for the rapids. To prove this case definitively, however, will require much more data on the geometry of the river corridor, the amount of alluvial fill within it, and the variability of both along the course of the river.

[52] Given the overall downcutting regime of the Colorado River in Grand Canyon since ~5 Ma, the present-day accumulation of tributary debris in the river channel must be an anomalous and transient condition. Because the great preponderance of the observable tributary debris in the Grand Canyon is late Quaternary, it seems likely that the present anomalous conditions are late Quaternary as well, perhaps commencing with the climatic changes at the Pleistocene–Holocene transition (~11 ka). So, too, was this a time of transition for the Colorado River, from a strong Latest Pleistocene river incising bedrock, powered by vast quantities of glacial meltwater, to a river increasingly burdened with tributary debris fill. Thus we imagine a Colorado River in Grand Canyon at ~11 ka that indeed was a bedrock river but with a river level meters to tens of meters lower than the present river level at those places affected by the present-day river profile convexities. Direct evidence supporting this model exists in late Pleistocene river gravels that are currently at or below river level at Palisades Creek and Tanner Canyon in ECC [*Hereford*, 1996] and at Granite Park in WCC [*Hereford et al.*, 2000].

[53] More generally, it seems likely that tributary debris can significantly influence main stem fluvial dynamics of any river system affected by high-relief, steep terrain; at least some lithologic types prone to slope failure; and even modest precipitation, as is the case for the Colorado Plateau. To the extent that debris flow activity is controlled by climatic fluctuations, we can expect such river systems to experience cycles of transient aggradation and incision. The Colorado River in Grand Canyon has been in a state of transient aggradation during the Holocene, which also seems to be the case for the Colorado River in Cataract

Canyon and the Green River in Dinosaur National Park, although age control of debris flow deposits in these reaches is limited.

[54] Indeed, deep, narrow bedrock canyons fed by high-relief, steep slope tributaries would seem to be necessary conditions for the processes we have discussed here leading to main stem aggradation caused by tributary debris flows. The high relief provides the potential energy to drive the debris flows to the river, but a narrow bedrock canyon plays an important role in confining not only the river but confining the effects of the debris flows on the river to the river.

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