Chapter 8:
Bedrock tributary incision, debris flows, and effects on the Colorado River in the Grand Canyon

JACOB SELANDER
DEPARTMENT OF GEOLOGY
UNIVERSITY OF CALIFORNIA, DAVIS, CA 95616
*JASELANDER@UCDAVIS.EDU

Introduction

Perhaps one of the most important drivers of landscape evolution are bedrock stream channels. These channels transmit signals of climactic or tectonic change across the landscape, control the timescale of response of the landscape to these changes, and can eventually set boundary conditions for hillslope processes and govern the height limits of mountain ranges (Seidl and Dietrich, 1992; Seidl, 1993; Howard et al., 1994; Sklar and Dietrich, 1998; Whipple and Tucker, 1999; Whipple et al., 2000, Selander, 2004). Bedrock-dominated fluvial channels are responsible for incision and channel lowering, which is widely studied and readily quantifiable (e.g. Stock and Montgomery, 1999; Kirby and Whipple, 2001; Dietrich et al., 2003).

Many studies have examined quantifying bedrock incision using empirical relationships defined by unit stream power and the stream power incision law (Whipple and Tucker, 1999; Dietrich et al., 2003; Whipple, 2004). These numerical models of channel evolution take into account numerous factors including channel slope, bedrock lithology, discharge/ stream velocity, and sediment supply.

Unit stream power can be expressed as work that a moving fluid does on a bedrock channel per unit area through the relationship:

$$\omega = \rho g Q S / W \qquad (1)$$

where ω is unit stream power, ρ is the density of the fluid (for example, water has a density of 1000 kg/m^3), g is the gravitational constant, Q is the discharge of the stream (m^3/s), S is dimensionless channel slope, and W is the width of the channel (m). Since the bedrock lowering or erosion rate of a channel is a function of the unit stream power, it can be expressed as the stream power incision law:

$$E = KA^m S^n \qquad (2)$$

where E is the erosion rate, A is the upstream drainage area (used as a proxy for discharge), S is the local channel slope, K is a coefficient of erosion (taking into account bedrock/ substrate properties), and m and n are empirically-derived exponents (see Whipple and Tucker, 1999 for a detailed explanation and derivation). These equations make the direct connection between erosion rate of a channel and its slope, discharge, and fluid density; increases or decreases in any of these variables directly relates to an increased or decreased incision rate.

Perturbations to a fluvial system such as changes in base level (e.g. main-stem incision) or lithology (e.g. competent vs. incompetent rock types) can create a locally over-steepened reach called a knickpoint (Figure 8.1). Channel incision is concentrated at knickpoints, creating an erosional "wave" that can propagate upstream (Selander, 2004; Whipple, 2004; Crosby et al., 2007).

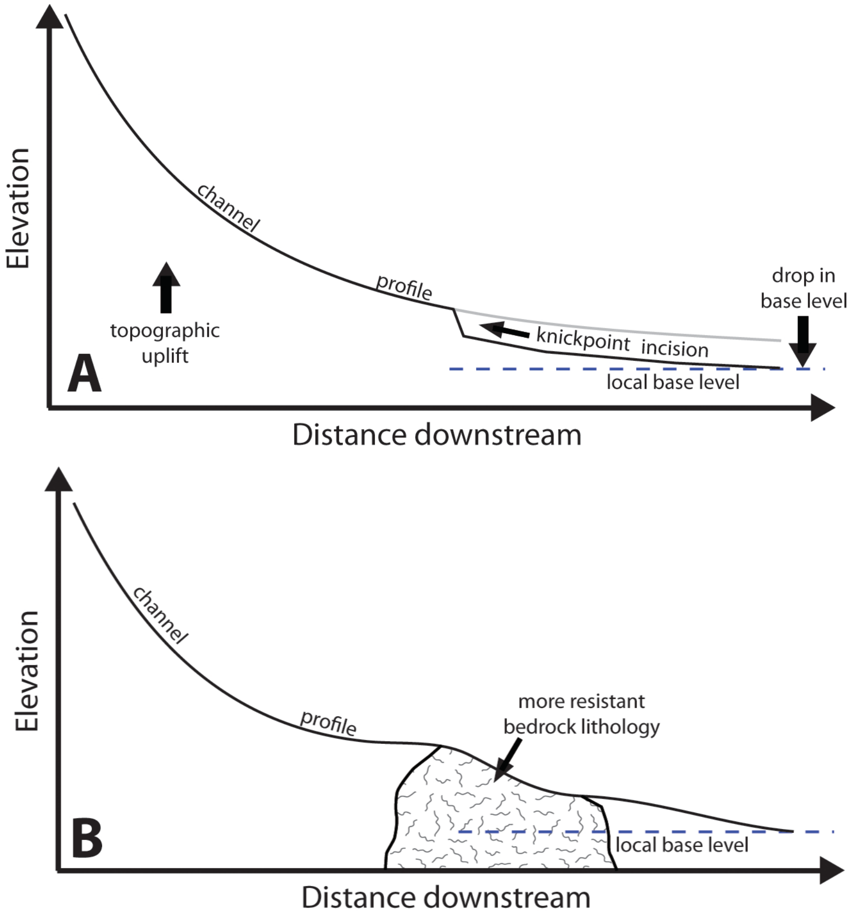

Figure 8.1. Schematic cartoon illustrating mechanisms to produce a locally-oversteepened reach (knickpoint) with concentrated erosion. **(A)** A drop in local base level (e.g. main-stem incision) will produce a knickpoint which will migrate upstream on tributaries. **(B)** Changes in bedrock lithology. More resistant lithologies require a higher amount of bed shear stress to erode (equation 1), which the channel adjusts to by increasing its local slope.

However, these incision laws only apply to a bedrock channel thalweg itself at slopes less than ~0.05-0.1%, where fluvial processes dominate (e.g. Stock and Dietrich, 2003). Above these slopes, drainage morphology is influenced by hillslope processes and debris flows. Debris flows can initiate when masses of loose sediment or colluvium become saturated with water and fail under gravitational forcing, moving downslope as a dense, non-Newtonian fluid (Iverson, 1997). Because debris flows are rarely mobile below slopes of ~0.02-0.05% (Stock and Dietrich, 2003 and references therein), as channel slopes drop below this threshold deposition of debris fans will occur.

Application to tributaries of the Colorado through the Grand Canyon

Late Quaternary incision rates on the main stem Colorado River in the eastern Grand Canyon range from ~0.1 – 0.4 mm/yr (Luchitta et al., 2000; Pederson et al., 2002). This incision has produced an erosional response on its tributaries (Karlstrom et al., 2008; Cook et al., 2009; Bennett, this volume; Longinotti, this volume). This response is manifested throughout the landscape as transient knickpoints developed on Colorado River tributaries (Figure 8.2) (Cook et al., 2009). These localized steep reaches concentrate tributary incision; the process by which this takes place will be discussed here.

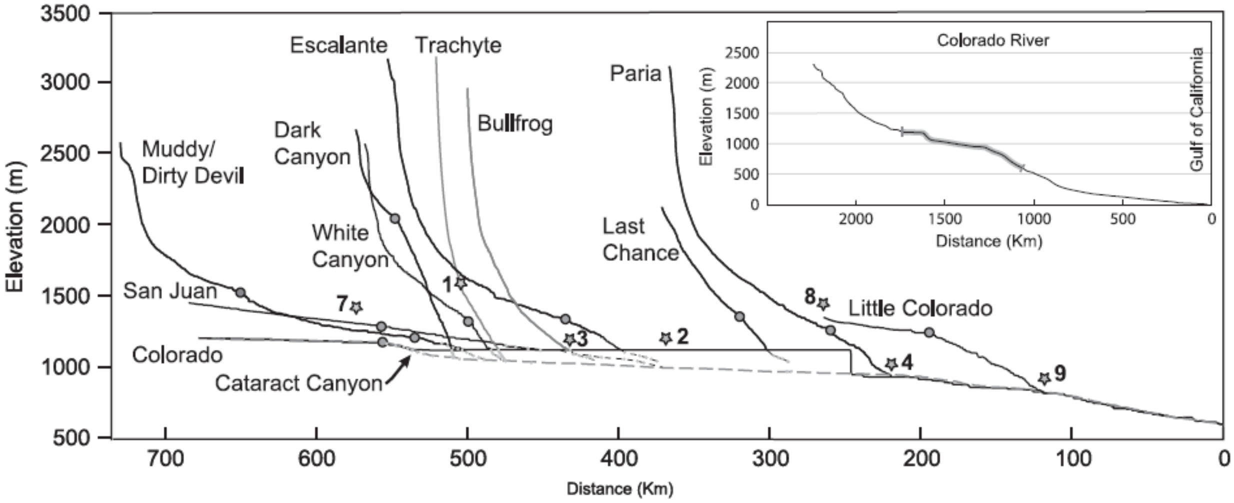

Figure 8.2. Long profiles of Colorado River tributaries between Cataract Canyon and the western Grand Canyon (from Cook et al., 2009). Circles on channel profiles indicate major knickpoints, consistent on all tributaries, stars locations of incision rate studies. Inset graph shows the longitudinal profile of the Colorado River from its source to the Gulf of California.

Due to the ephemeral nature of tributaries of the Colorado River, high-discharge events happen as episodic debris flows (Figure 8.3) (Howard and Dolan, 1981; Webb et al., 1999; 2000; Griffiths et al., 2004). These debris flows occur when concentrated rainfall or flash flood events trigger slope failures, creating high-density, high-discharge, poorly-sorted, slurry-like (>25% water) flows that can move large amounts of material (Cerling et al., 1999). Estimates of individual flow volumes range from 300 to 65,000 m^3 (Webb et al., 2000; Griffiths et al., 2004) with velocities upwards of 4 m/s, capable of moving clasts over 8000 kg (Webb, 1987). It is these events that create discharges and velocities ultimately responsible for channel lowering and sediment flux into the main Colorado River.

740 individual tributaries contribute sediment to the Colorado River through debris flows. Synthesis of historical records of debris flows in the Grand Canyon show a recurrence interval of ~5 events per year (from Lees Ferry downstream) (Griffiths et al., 2004). Studies of debris fans at individual catchment show a record of debris flow events extending through the Holocene (e.g. Hereford et al., 1996; Cerling

et al., 1999). For example, the mouth of Prospect Canyon, co-located with the notorious Lava Falls rapid (Figure 8.3), contains multiple generations of debris fans recording 12 major, fan-forming events over the past 10 kyr (Cerling et al., 1999).

Figure 8.3. Photograph of debris fans at the confluence of Prospect Canyon and the Colorado River (from Cerling et al., 1999). Note the flat morphology of the fan tops, and the multiple generations of debris fans present.

Debris flow initiation on Grand Canyon tributaries is highly controlled by stratigraphy. Examination of material in debris fans has shown that principal sources of many debris flows are the weaker shale and sandstone members of the Supai and Tonto Groups (Griffiths et al., 2004, Garber, this volume; Kercher, this volume). These weakly indurated, hillslope-forming units are more susceptible to oversaturation by water during intense rainfall events, and subsequent slope failure (Griffiths et al., 2004 and references therein). Once initiated, these slope failures move into the tributary channel, gaining velocity and the competence to entrain large amounts of material (e.g. Iverson, 1997).

Effects on the main stem Colorado River

Tributary debris flows have a profound effect on the morphology of the Colorado River in the Grand Canyon. Perhaps the most notable is the effect debris fans have on the longitudinal profile of the Colorado (e.g. Graf, 1979; Hanks and Webb, 2006; Bartolomeo, this volume). Large debris fans input extremely coarse sediment into the Colorado, with grain sizes well above the competence of the Colorado during flood events. These local areas of coarse sediment are capable of reducing the upstream gradient of the Colorado, causing it to lose a portion of its suspended load (Hanks and Webb, 2006). At the debris fans (co-located at tributary junctions), the Colorado loses gradient abruptly in the form of rapids (Figures 8.4 and 8.5) (e.g. Graf, 1979; Griffiths et al., 2004; Bartolomeo, this volume). These rapids at tributary junctions account for ~66% of the gradient within the Grand Canyon, but only 9% of total downstream length (Griffiths et al., 2004). The low-velocity regions created above and below debris fans and associated rapids additionally create biological habitats (see Bartolomeo; Lusardi; Oliver, Cookingham; and Hartman, this volume for details).

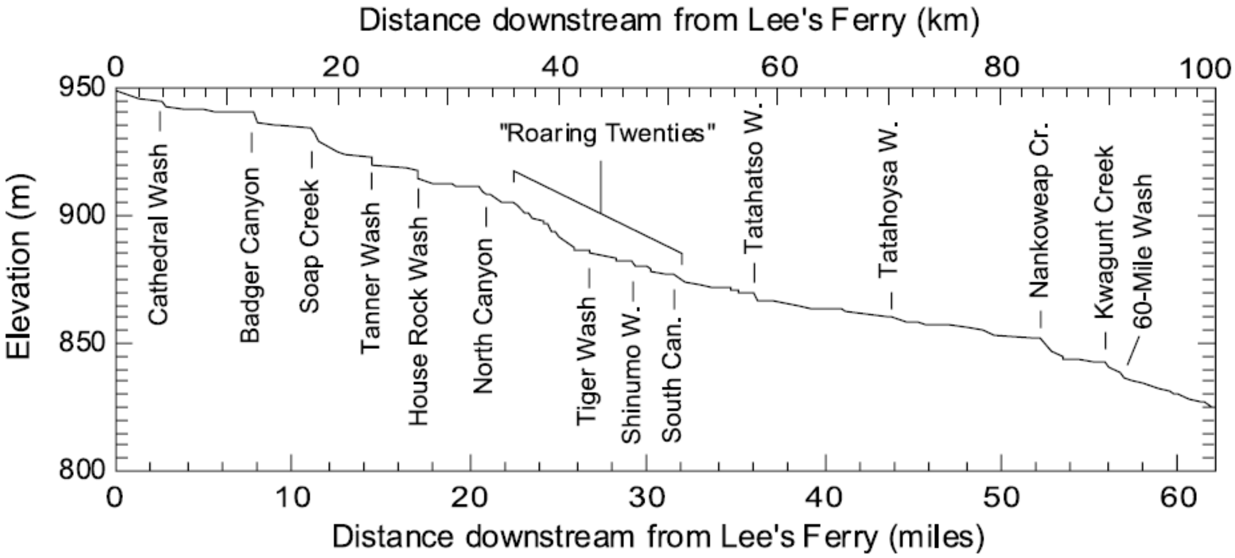

Figure 8.4. Longitudinal profile of the Colorado River between Lee's Ferry and the confluence of the Little Colorado River (from Griffiths et al., 2004). Note the distinct low-gradient reaches above and steep reaches (rapids) at tributary junctions.

Debris flows on tributaries are the main source of sediment input (>80%) to the Colorado River through the Grand Canyon (Webb, 1987; Yanites et al., 2006; Webb et al., 1999; Gibson, this volume). Prior to the construction of Glen Canyon Dam, the Colorado River removed or reworked most debris deposits during flood events that ranged from 2330 – 6300 m^3/s, capable of moving all but the largest particles (Webb et al., 1999). Following regulation of the Colorado discharge (e.g. Burley; Gibson, this volume), the discharge remained insufficient to erode debris fans (Webb et al., 1999). Experimental high-flow events (Burley, this volume) in the past 50 years have only re-worked a small number of debris fans, others have continued to aggrade and further perturb the local hydraulic geometry of the Colorado River (Yanites et al., 2006).

Summary

Bedrock tributary incision throughout the Grand Canyon is driven by episodic debris-flow processes, and is the primary source of sediment input to the Colorado River downstream of Glen Canyon Dam. Initiation of these flows is highly controlled by the stratigraphy of the Grand Canyon, and their fan deposits control local hydraulic geometry of the Colorado River creating rapids at tributary junctions. Debris fans at present are continuing to aggrade and modify the Colorado channel, as regulated discharge on the Colorado River is rarely sufficient enough to move the coarse particles composing these fans.

Figure 8.5. Channel and rapid morphology at Granite Rapid (from Griffiths et al., 2004), typical of rapids in the Grand Canyon. (1) notes a tributary debris fan blocking the main stem Colorado River; (2) is the rapid formed by constriction of the Colorado and forced local steep reach; (3) is a downstream debris island; (4) is a minor rapid produced by constriction adjacent to the downstream debris bar. Black arrow indicates direction of flow.

References

Cerling, T.E., Webb, R.H., Poreda, R.J., Rigby, A.D., and Melis, T.S. (1999) Cosmogenic ^{3}He ages and frequency of late Holocene debris flows from Prospect Canyon, Grand Canyon, USA, *Geomorphology*, 27, p. 93-111.

Cook, K.L., Whipple, K.X., Heimsath, A.M., and Hanks, T.C. (2009) Rapid incision of the Colorado River in Glen Canyon- Insights from channel profiles, local incision rates, and modeling of lithologic controls, *Earth Surface Processes and Landforms*, 34, p 994-1010.

Crosby, B.T., Whipple, K.X., Gasparini, N.M., and Wobus, C.W. (2007) Formation of fluvial hanging valleys: Theory and simulation, *Journal of Geophysical Research*, 112, F3, doi: 10.1029/2006JF000566.

Dietrich, W.E., Bellugi, D., Heimsath, A.M., Roering, J.J., Sklar, L., Stock, J.D. (2003) Geomorphic transport laws for predicting the form evolution of landscapes. In *Prediction in Geomorphology*, ed. P.R. Wilcock, R. Iverson, pp. 103–32. Washington, DC: Am. Geophys. Union

Graf, W.L. (1979) Rapids in canyon rivers, *Journal of Geology*, 87, p. 533-551.

Griffiths, P. G., R. H. Webb, and T. S. Melis (2004), Frequency and initiation of debris flows in Grand Canyon, Arizona, *Journal of Geophysical Research*, 109, F04002, doi:10.1029/2003JF000077.

Hereford, R., Thompson, K.S., Burke, K.J., Fairley, H.C., (1996) Tributary debris fans and the late Holocene alluvial chronology of the Colorado River, eastern Grand Canyon, Arizona. *Geological Society of America Bulletin*, 108, p. 3–19.

Howard, A., and R. Dolan (1981), Geomorphology of the Colorado River in Grand Canyon, *Journal of Geology*, 89, 269– 297.

Howard, Alan D., Dietrich, William E. and Seidl, Michelle A. (1994) Modeling fluvial erosion on regional to continental scales, *Journal of Geophysical Research*, (99) no. B7, p. 13,971-13,986.

Iverson, R.M. (1997) The physics of debris flows, *Reviews of Geophysics*, 35 (3) p. 245-296.

Karlstrom, K.E., Crow, R., Crossey, L.J., Coblentz, D., Van Wijk, J.W. (2008) Model for tectonically driven incision of the younger than 6 Ma Grand Canyon. *Geology*, v. 36, p. 835–838. DOI: 10.1130/G25032A.1

Kirby, E. and Whipple, K. (2001) Quantifying differential rock-uplift rates via stream profile analysis, *Geology*, v. 29, no. 5, p. 415-418.

Pederson, J., Karlstrom, K., Sharp, W., McIntosh, W. (2002) Differential incision of the Grand Canyon related to Quaternary faulting – Constraints from U-series and Ar/Ar dating. *Geology,* v. 30, p. 739–742.

Lucchitta, I., Curtis, G.H., Davis, M.E., Davis, S.W., Turrin, B. (2000) Cyclic aggradation and downcutting, fluvial response to volcanic activity, and calibration of soil-carbonate stages in the western Grand Canyon, Arizona. *Quaternary Research* **53**: 23–33.

Seidl, Michelle A. and Dietrich, William E. (1992) The problem of channel erosion into bedrock, Functional Geomorphology; Landform Analysis and Models, Catena supplement 23, p. 101-124.

Seidl, Michelle A. (1993) *Form and process in channel incision of bedrock*. University of California at Berkeley Ph.D. thesis, Berkeley, California.

Selander, J.A. (2004) *Processes of knickpoint propagation and bedrock incision in the Oregon Coast Range.* University of Oregon B.S. thesis, Eugene, Oregon.

Sklar, Leonard and Dietrich, William. (1998) River longitudinal profiles and bedrock incision models: Stream power and the influence of sediment supply, *in* Tinkler, K. and Wohl, E.E., eds., Rivers over rock: Fluvial processes in bedrock channels: Washington D.C., American Geophysical Union, Geophysical Monograph 107, p. 237-260.

Stock, Jonathan D. and Montgomery, David R. (1999) Geologic constraints on bedrock river incision using the stream power law, *Journal of Geophysical Research*, v. 104, no. B3, p. 4983-4993.

Stock, J., and W. E. Dietrich, (2003) Valley incision by debris flows: Evidence of a topographic signature, *Water Resources Research*, v. 39, no. 4, doi:10.1029/2001WR001057

Whipple, Kelin X. and Tucker, Gregory E. (1999) Dynamics of the stream-power incision model: Implications for height limits of mountain ranges, landscape response timescales, and research needs, *Journal of Geophysical Research,* v. 104, no. B8, p. 17.661-17,674.

Whipple, Kelin X., Hancock, Gregory S., Anderson, Robert S. (2000) River incision into bedrock: Mechanics and relative efficacy of plucking, abrasion and cavitation, *Geological Society of America Bulletin*, v. 112, no. 3, p. 490-503.

Webb, R.H. (1987) Debris flows from tributaries of the Colorado River, Grand Canyon National Park, Arizona, USGS Open-File Report 87-117.

Webb, R. H., P. G. Griffiths, T. S. Melis, and J. G. Elliott, (1999) Reworking of aggraded debris fans, *in* the Controlled Flood in Grand Canyon, Geophysical Monograph 110, American Geophysical Union

Webb, R. H., P. G. Griffiths, T. S. Melis, and D. R. Hartley (2000), Sediment delivery by ungaged tributaries of the Colorado River in Grand Canyon, Arizona, U.S. Geol. Surv. Water Resour. Invest. Rep., 00-4055, 67 pp.

Whipple, K.X. (2004) Bedrock rivers and the geomorphology of active orogens, *Annual Review of Earth and Planetary Science* (32) p. 151-185, doi:10.1146/annurev.earth.23.101802.120356

Yanites, B. J., R. H. Webb, P. G. Griffiths, and C. S. Magirl (2006), Debris flow deposition and reworking by the Colorado River in Grand Canyon, Arizona, *Water Resources Research*, v. 42, W11411, doi:10.1029/2005WR004847.