Dynamics and Evolution of Tributary Alluvial Fans in the Grand Canyon below Glen Canyon Dam

Alex Morelan

Abstract/ Introduction:

Tributary alluvial fans along the Grand Canyon are key to both natural and boater habitat. The primary influence that tributary fans have on the river is as source of sediment input and constriction of main stem flow. The sediment is delivered largely as debris flows: a mix of water, mud, and boulders that often behaves as a non-Newtonian fluid. Because of the unique mechanical attributes of debris flows, they can transport large boulders long distances. This ability to transport boulders becomes important for understanding how tributary alluvial fans influence habitat along the Colorado River at the bottom of the Grand Canyon. As tributary alluvial fans form in the canyon bottom, they constrict the flow of the river forming rapids at the toes of the fans and eddies above and below the constriction (figure 1) (Yanites et al., 2006). Boulders sourced from the fan toe contribute to turbulence in rapids (Hanks and Webb, 2006). Since the completion of Glen Canyon Dam, the dynamics of sediment transport have been significantly interrupted. Large annual variation in flow rate (maximum annual flows up to ~100,000 ft^3/s, with an historical record above 300,000 ft^3/s) of the Colorado River has been replaced by daily fluctuations (maximum up to ~10,000 ft^3/s) as a function of energy prices (Dolan et al., 1974). In the last 20 years annual (1-week duration) high flow events (HFEs) have attempted to mimic pre-dam dynamics (maximum ~50,000 ft^3/s) (Alvarez and Schmeeckle, 2013). These HFEs are called upon to serve many functions (including building high sand bars) but have not necessarily been successful in maintaining anything resembling a natural (pre-dam) system. The replacement of historic annual variation with modern high frequency, low-amplitude variation has significantly changed how tributary alluvial fans deliver sediment and interact with the main channel of the Grand Canyon.

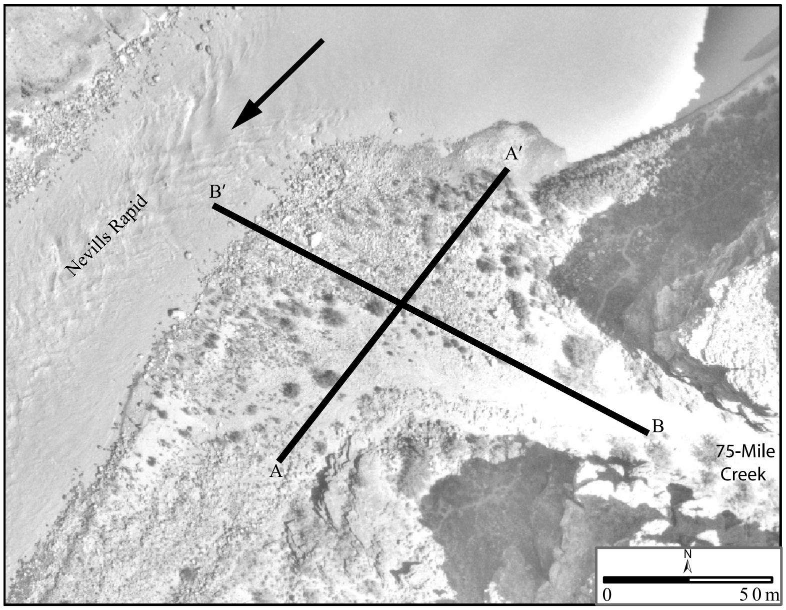

Figure 1: Tributary alluvial fan from 75-mile creek constricting the main stem of the Colorado River forming Nevills Rapid (from Yanites et al., 2006)

Alluvial fan deposition:

Alluvial fans form when a channel exiting a range front loses its confinement and the velocity of the of channel decreases as a result of the increase of the cross-sectional area of the channel and the sediment load is deposited (figure 2) (Bull, 1977). An alluvial fan is a subaerial

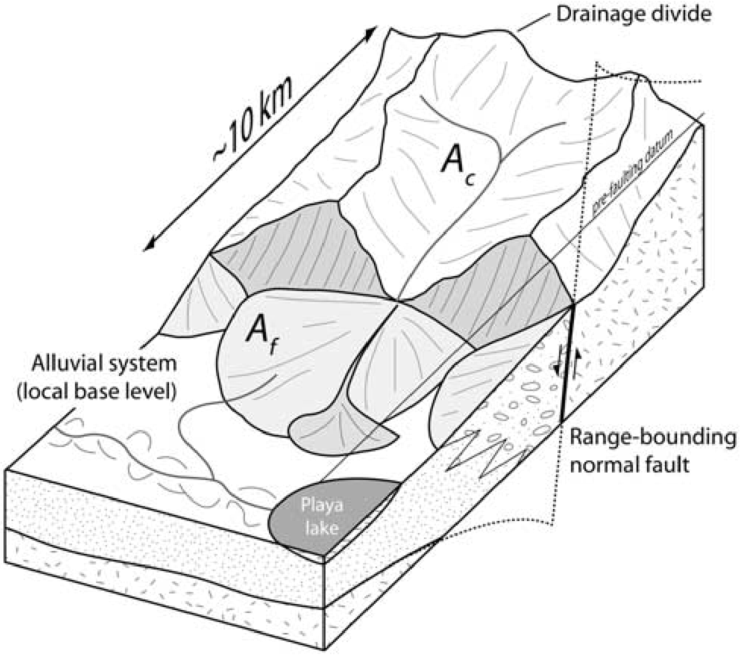

Figure 2: Diagram of alluvial fan formation at a range front. In this example, the range front fault provides accommodation space, in the Grand Canyon, accommodation space is formed by Colorado River incision (from Densmore et al., 2007)

fan deposit (literally means deposited "below the air") as opposed to a delta, which is a subaqueous fan deposit (below water). The first-order morphology and mechanics of these two systems resemble one another, but in detail the mechanisms of deposition and the sediment deposited are quite distinct. Deltaic deposits form in an environment with a significantly smaller density contrast between the sediment and overlying substrate (sediment vs. water and sediment vs. air) (Edmonds et al., 2011). This difference in density contrast affects the variation in grain sizes deposited, the morphology of the fan, and the mechanics behind how the sediment accumulates (related to the morphology). Deltas continuously prograde into the basin as long as the base level (sea or lake level) stays constant (figure 3a). Progradation occurs as sediment accumulates at the point in the system where the channel loses its velocity at the edge of the basin into which it is being deposited (Edmonds et al., 2011). When the sediment pile reaches the angle of repose (the steepest a sediment pile can get before it collapses, usually around 35 degrees), it is transported down the active slope of the subaqueous fan until it reaches the toe of the fan at which point the slope is too low for transport. As soon as the sediment reaches this point down-fan, it stops flowing out and becomes the toe of the deposit. The delta grows as the point of deposition at the mouth of the channel moves outward into the basin on top of earlier deposits (figure 3a). Deltas have flat tops at the elevation of the water into which it is deposited. In map view (from above), deltas are fan-shaped with the source channel being the origin of the fan. Alluvial fan deposition is similar in that deposition occurs as the channel leaves a confined upstream source. Alluvial fans also have a fan shape in map view. Alluvial fans form below the angle of repose because deposition occurs continuously down-fan. After the channel leaves confinement downstream in an alluvial system, sediment transport continues while deposition occurs. Because this is a continuous process, alluvial fans have some degree of sorting with larger grain sizes more commonly deposited near the mouth of the channel and finer grains towards the toe of the fan (Hooke, 1967). This complicating factor results in alluvial fan deposits being relatively heterogeneous with large and small grain sizes present throughout most of the system and layered sediments in cross-section (figure 3b). When observing the down-fan sorting present in alluvial fans, it its important to consider the control that debris flows impart on the system. If debris flows are common (little time between them), the grain size variation down-fan may not be obvious. The sorting and transport of smaller grains down-fan also occurs when material at the top of the fan is reworked by non-debris flows (dominantly water). If reworking between debris flows is uncommon (in arid environments), then the majority of the surface of the fan will be dominantly unsorted with a mix of large and small grains present in most places.

Although there exist alluvial fans in a range of climatic environments, with each environment contributing unique controls on fan development and architecture (here architecture refers to the stratigraphic pattern), this paper will focus on arid alluvial fans- the climate and therefore fan type found in the Grand Canyon. The stratigraphy of an arid alluvial fan reveals the conditions under which the fan deposit formed (Blair, 1999). Generally, arid alluvial fans consist of poorly sorted sediment with grain sizes ranging from fine sand (<mm) to boulders (m<) (figure 4). These grains and clasts (pieces of rock) are deposited in down-slope lobes each time a debris flow mobilizes sediment from a catchment due to a precipitation or snowmelt event.

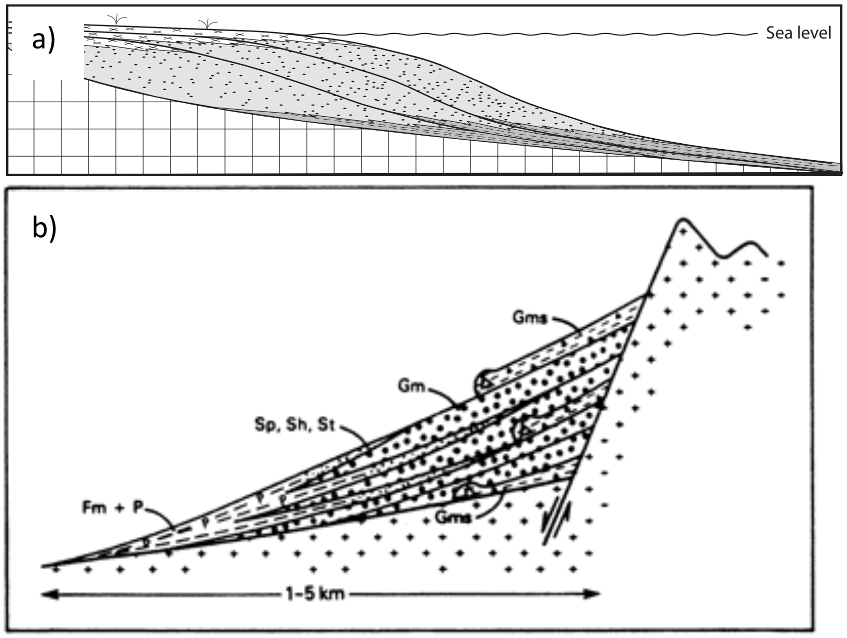

Figure 3a: a) Cross section of delta formation. Note how beds deposit into the basin with the top of every bed at the same elevation at sea level (from Edmonds et al., 2011) b) Cross section of alluvial fan stratigraphy. Note much more complex stratigraphy and how change in base level affects the interfingering with the basin (from Rust and Koster, 1984).

Tributary Alluvial Fans in the Grand Canyon:

Conditions Before Glen Canyon Dam

Before the installation of Glen Canyon Dam, the Colorado River was veritably wild, with large annual variations in flow (reported ranging from less than 5,000 ft^3/s to greater than 300,000 ft^3/s) and continuously carrying a significant sediment load. The annual spring floods on the river served many functions. Floods transported sediment through the system, depositing sand bars and terraces high on the sides of the canyon (Hanks and Webb, 2006). Because these deposits lie above the river level for most of the year, they were relatively stable as small fluctuations in river level and continuous flow could not reach them. These deposits served as habitat for riparian vegetation and therefore habitat for birds. Importantly, the large annual floods translated sediment from the toes of tributary alluvial fans. Also, these large floods were likely the only flows that could move large boulders out of rapids (Hanks and Webb, 2006). According to early observations and historical photography, the deposits along the river level, in many places tributary alluvial fans, were mostly not vegetated due to the large annual floods preventing substantial (woody) species from establishing. The dominant kinds of vegetation on low-level (near river elevation) deposits were grass species that quickly established between annual flood events.

The sediment transport characteristics of the Colorado River, especially where the sediment load was sourced, were significantly different before the establishment of Glen Canyon Dam. The median sediment concentration at Lees Ferry before the establishment of the dam was measured at 1,500 ppm (Howard and Dolan, 1981). In high-flow events, the concentration of sediment reached 21,000 ppm at least 1% of the time. The nature of sediment mobilization through the system was probably a gradual deposition and entrainment process as sedim ent translated down stream. A certain thickness of sediment on the bottom of the channel was maintained down the length of the river before the dam was built.

Figure 4: Typical coarse deposit of an arid alluvial fan. Notice the range in grain sizes present in this deposit. Gravels mix with sand and cobbles as debris flows travel down the fan. Note that other parts of this same fan contain different grain size distributions (from Blair, 1999)

Effects of Glen Canyon Dam

The completion of Glen Canyon Dam resulted in the taming of the Colorado River through the Grand Canyon. A significant effect of the dam is that sediment is deposited at the inlet to the reservoir, more than a hundred miles upstream of the outlet. This means that any sediment that used to flow through the system from above dam is now trapped in the reservoir. Because of the large storage capacity of the reservoir, the flow rate of the Colorado River is now entirely under dam regulated control (except when near capacity and the input to the reservoir is too high, such as in the 1983 floods). The flow rate of the Colorado River now tracks energy prices because of hydroelectric power generation. At times when the price of energy is high (during the day) water is released through the dam to create energy. As the price of energy drops at night, the flow is decreased. Daily variations are often two-fold in flow rate (as of March 1, 2015 the daily flow varied between ~7,000 ft^3/s to ~13,000 ft^3/s). The large annual variation in the system has been replaced by a relatively low-amplitude, high frequency variation.

The human control over the Colorado River flow rate has significantly changed how sediment moves through the system as well as how the landforms altered by the flow of the river evolve. The new flow regime has had three main effects on landforms in the Grand Canyon. The first is the lack of very high flows that deposit terraces, sand bars, and bury vegetation at low river level. Second, high flows do not move boulders out of rapids at tributary fans. Third, high frequency river-level changes erode deposits at river level at a more rapid rate. An aspect of this system to consider, along with the flow rate variation, is that the sediment concentration is greatly reduced because of sediment capture at the inlet of the reservoir far upstream of the dam. The significant reduction in sediment concentration means that the tributaries' contribution to the sediment in the Colorado River is significantly greater. This also results in less sediment stored on the bed at any given time. Because of the documented effects of the lack of high flows, management of the flow rate has recently been designed to attempt to remedy some of the negative outcomes of human control of the flow rate.

High-flow Experiments (HFEs)

High-flow experiments (HFEs) were established in the 1990s initially to mimic spring flood events (Alvarez and Schmeeckle, 2013). The first experiment successfully deposited high bars and terraces but flows were still substantially below historically documented annual flood events. Unfortunately, the pulse of release was very sudden with flow dropping off very suddenly back to the high frequency, low amplitude daily variation. The result was that sand bars built in the flood eroded quickly due the sharp drop in flow and the daily flow variation. Subsequent HFEs have compensated by using a more natural flow profile with a significant heavy tail to mimic natural floods. These subsequent HFEs have produced more stable bars but reports indicate that they still do not effectively bury the vegetation enough to restore pre-dam conditions. The maximum flows of HFEs are reported to be ~50,000 ft^3/s. This value is still less than half of the flow rate of an annual flood (and far less than the recorded maximum flow of

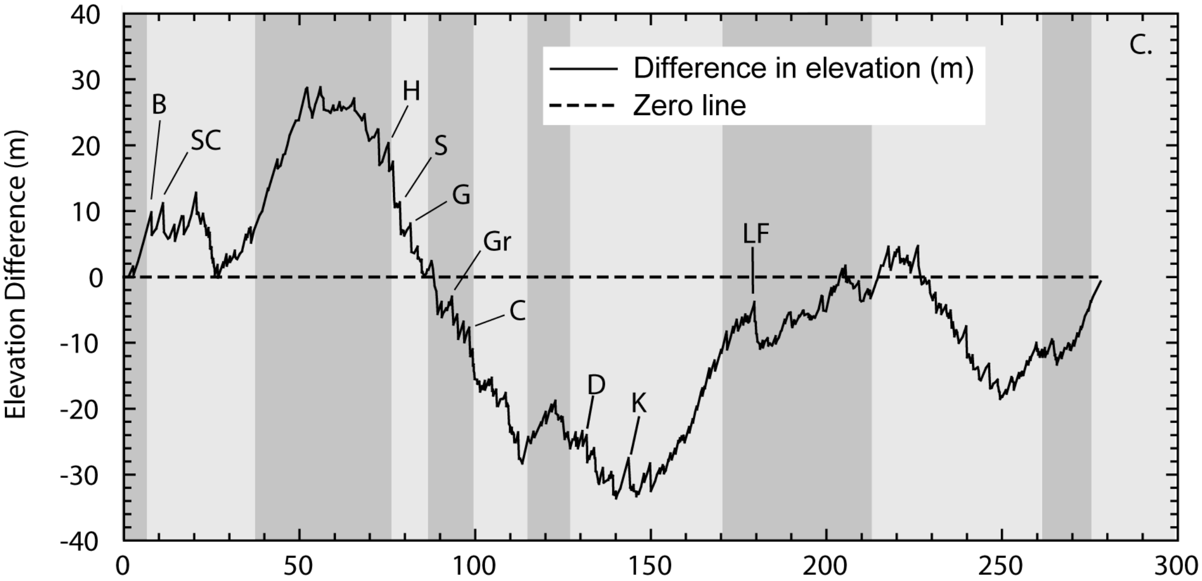

Figure 5: This figure shows the deviation of the river profile from a linear slope down the Grand Canyon. The letters correspond to rapids. The important thing to note is how steeply the profile drops at each rapid and the relatively gentle gradient between the rapids. The longer wavelength variation is due to differential incision of the canyon bottom because of knick points traveling up the canyon from a combination of far field base level change and lithological contrasts that cause the canyon to erode at different rates (from Hanks and Webb, 2006).

300,000 ft^3/s). It is unlikely that these flows are able to translate boulders through rapids. Because boulders have accumulated in rapids, the percentage of the river fall (where how much of the drop happens) in rapids has increased (figure 5) (Hanks and Webb, 2006). This basically means that the rapids have gotten steeper and the gentler sections of river between the rapids have gotten flatter. Before the dam was constructed, the large flows moved boulders out of rapids making rapids less steep and increasing the slope of the gentle sections between the rapids.

Conclusions:

Tributary alluvial fans in the Grand Canyon are important components in the sediment transport framework, especially since the completion of Glen Canyon Dam. Tributary fans constrict the main stem of the Colorado River producing rapids as well as flat water with eddies above and below the constriction. These calmer pools serve as habitat for freshwater fish. The sediment deposits lain by the tributary alluvial fans serve both as boater habitat and substrate for vegetation. Significant changes have occurred in the system since the dam was built. Large floods no longer wash boulders out of rapids at the constrictions due to tributary alluvial fans. Now that sediments transported by the main stem Colorado River are trapped at the inlet to Lake Powell, the only sources of sediments down stream of Glen Canyon Dam are the tributary alluvial fans.

References:

Alvarez, L. V., and Schmeeckle, M.W., 2013, EROSION OF RIVER SANDBARS BY DIURNAL STAGE FLUCTUATIONS IN THE COLORADO RIVER IN THE MARBLE AND GRAND CANYONS: FULL-SCALE LABORATORY EXPERIMENTS: River Research and Applications, v. 29, no. 7, p. 839–854, doi: 10.1002/rra.2576.

Blair, T.C., 1999, Sedimentology of the debris-flow-dominated Warm Spring Canyon alluvial fan, Death Valley, California: Sedimentology, v. 46, no. 5, p. 941–965, doi: 10.1046/j.1365-3091.1999.00260.x.

Bull, W.B., 1977, The alluvial-fan environment: Progress in Physical Geography, v. 1, no. 2, p. 222–270, doi: 10.1177/030913337700100202.

Densmore, A.L., Allen, P.A., and Simpson, G., 2007, Development and response of a coupled catchment fan system under changing tectonic and climatic forcing: Journal of Geophysical Research, v. 112, no. F1, p. F01002, doi: 10.1029/2006JF000474.

Dolan, R., Howard, A., and Gallenson, A., 1974, Man's Impact on the Colorado River in the Grand Canyon: The Grand Canyon is being affected both by the vastly changed Colorado River and by the increased presence of man: American Scientist, p. 392–401.

Edmonds, D.A., Shaw, J.B., and Mohrig, D., 2011, Topset-dominated deltas: A new model for river delta stratigraphy: Geology, v. 39, no. 12, p. 1175–1178, doi: 10.1130/G32358.1.

Hanks, T.C., and Webb, R.H., 2006, Effects of tributary debris on the longitudinal profile of the Colorado River in Grand Canyon: Journal of Geophysical Research, v. 111, no. F2, p. F02020, doi: 10.1029/2004JF000257.

Hooke, R.L., 1967, Processes on Arid-Region Alluvial Fans: The Journal of Geology, v. 75, no. 4, p. 438–460, doi: 10.2307/30085004.

HOWARD, A., and DOLAN, R., 1981, GEOMORPHOLOGY OF THE COLORADO RIVER IN THE GRAND-CANYON: JOURNAL OF GEOLOGY, v. 89, no. 3, p. 269–298.

Rust, B.R., and Koster, E.H., 1984, Coarse alluvial deposits, *in* Facies models, Geological Association of Canada Toronto, p. 53–69.

Yanites, B.J., Webb, R.H., Griffiths, P.G., and Magirl, C.S., 2006, Debris flow deposition and reworking by the Colorado River in Grand Canyon, Arizona: Water Resources Research, v. 42, no. 11, p. n/a–n/a, doi: 10.1029/2005WR004847.