Aggradation, flooding, thresholds: a review of avulsion dynamics on alluvial fans

Anya Leenman, University of British Columbia

1. Introduction
Alluvial fans are semi-circular depositional landforms, found at mountain fronts, tributary junctions, or hillslope-channel transitions (Harvey, 2010; 2012). This essay considers avulsion on alluvial fans. Avulsion is a wholesale shift in channel position, and is usually instantaneous relative to the interavulsion period. Along with sheetflow, it is one of the primary mechanisms by which fans build their characteristic semi-circular form (Blair and McPherson, 1994; Parker et al., 1998).

There are numerous motivations for the study of avulsion on fans. Foremost among these is the need to understand avulsion probability, with a view to characterising geohazards on fans. Fans are popular sites for settlement, particularly in mountainous regions such as British Columbia and Alberta (Cavalli and Marchi, 2008; Kellerhals and Church, 1990; Santangelo et al., 2012; Schick et al., 1999). Avulsions on fans can thus have catastrophic results; a famed example was the 2008 avulsion on the Kosi megafan (India), that affected > 30 million people (Sinha, 2009).

This essay begins by considering internal and external controls on fan-channel avulsions. The processes that precondition and eventually trigger avulsions are differentiated, and key drivers of avulsion are discussed. The application of these ideas to alluvial fans in BC is then briefly considered.

This essay does not consider fans built by debris flow. Although these are also highly active systems, the magnitude and frequency of channel forming events are different, so that avulsion setup and trigger processes differ. This essay primarily considers fully fluvial (i.e. streamflow dominated) fans.

2. Internal and external controls
In geomorphic systems, controlling or forcing variables can be considered internal or external to a system. External forcings are a system's “boundary” conditions; for alluvial fans, this includes climate, tectonics, base level, and sediment and water discharge from a fan’s feeder catchment (Clarke et al., 2010). Internal forcings often operate via thresholds and feedbacks; for example, alluvial fans are often regulated by their own gradient, so that gradient change past a threshold can lead to a switch from erosion to deposition, or vice versa (Clarke et al., 2010; Schumm, 1973).

Early experiments showed that, even with constant flow and sediment supply, fans evolved through an internally generated (“autogenic”) cycle of erosion and deposition (Schumm et al., 1987). Initially, the fan-head was trenched (Figure 1, a); sediment bypassed the upper fan to be deposited in a lobe at the fan-front. The fan-channel would gradually back-fill with sediment (b), with the sedimentation zone moving up-fan. Eventually, flow spread at the fan-head (c), with deposition at the fan-head increasing fan slope. Ultimately, the fan oversteepened and a new channel was cut (d), repeating the cycle (e, f). The key variable moderating this cycle was gradient (of both fan and channel). Deposition was initiated by low gradient in the fan-front lobes, and incision by fan-head oversteepening. Many other experiments exhibited this cycle (e.g. Clarke et al., 2010; Hooke and Rohrer, 1979; Whipple et al., 1998). Some also featured sheetflow during the unchannelised, depositional stage (Clarke et al., 2010; Van Dijk et al., 2012).
This cycle is complicated by temporal variation in external conditions, such as climate or tectonics (Bull, 1964; Eckis, 1928; Harvey, 1978; Lustig, 1965). Changes to sediment and water supply can initiate periods of incision (trenching) or aggradation, depending on the sediment:water ratio of flow (Lustig, 1965; Wells and Harvey, 1987). These changes could be long-term (in the case of climate change), or rapid and dramatic. For instance, sediment supplied from a landslide upstream can rapidly fill a trenched fan-channel and oversteepen the fan-head, increasing the avulsion probability (Davies and Korup, 2007).

Understanding avulsion on fans is made more difficult by the fact that avulsion can be internally or externally driven. For example, Van Dijk et al. (2009) observed that in experimental fan-deltas with constant inputs of water and sediment, ~60% of autogenic cut-and-fill deposits were preserved. They argued that externally driven cut-and-fill cycles had a similar preservation potential, prompting concern over the attribution of cause and effect in stratigraphic interpretations. Likewise, Straub and Wang (2013) estimated that in fan-deltas, autogenic dynamics operate on timescales of up to 150 years – during which external forcings could change considerably. These studies highlight that cutting or filling on fans should not be attributed solely to external conditions, given the clearly demonstrated magnitude of internal fan dynamics involving feedbacks and thresholds (Harvey, 1978; Ventra and Nichols, 2014).

3. Avulsion setup and trigger

Figure 1: The Schumm et al. (1987) schematic diagram of the autogenic cycle of trenching (a), lobe deposition (a), back-filling (a-c), flow spreading (c) and eventual avulsion (c-d).

Figure 2: Jones and Schumm’s (1999) conceptual model of channel preconditioning by a series of floods; as the channel nears the avulsion “threshold”, avulsion can be caused by a flood of moderate magnitude.
The back-filling observed by Schumm et al. (1987) (Figure 1, a-c) preconditions a fan-channel through aggradation, priming it for eventual avulsion. Jones and Schumm (1999) presented the idea of an avulsion “threshold”, with processes which increase channel instability (such as aggradation) bringing a channel closer to this threshold. As a channel approaches the threshold, the flood magnitude required to cause avulsion decreases (Figure 2). Slingerland and Smith (2004) continued these ideas, dividing the processes that cause avulsion into two categories: “setup” and “trigger”. Back-filling and aggradation (processes that prime a channel for avulsion) are the avulsion “setup”, while the flood that causes avulsion is the “trigger”.

These ideas were supported by observations of Field (2001) on natural fans in Arizona. He found that it was not simply large floods which caused avulsion; rather, low-magnitude, high-frequency floods gradually filled channels, reducing their capacity. Had aggradation not occurred, a large channel capacity would be maintained and high discharges conveyed, without causing overbank flow and avulsion.

4. Drivers of avulsion
Since 1995, interest in the drivers of avulsion setup in fans has intensified. This work has developed more quantitative understandings of the controls on avulsion. Some of these controls are explored below.

4.1 Sediment supply
Experiments show that avulsion frequency increases with sediment supply (Ashworth et al., 2004; Bryant et al., 1995). Bryant et al. (1995) found that as sediment supply increased, the volume of sediment needed to trigger avulsion decreased, so avulsion frequency increased “faster than linearly” with sedimentation rate. Ashworth et al. (2004) investigated avulsion in braided rivers. Although they observed that avulsion frequency increased with sediment supply, the rate was slower than a 1:1 relationship, contrasting the Bryant et al. (1995) experiments. They attributed this difference to an order-of-magnitude reduction in gradient and sediment supply in their own experiments. The latter two variables are related; Whipple et al. (1998) found that higher sediment supply generated steeper fans. Ultimately, we need further research to ascertain if braided rivers and alluvial fans are end members of the same spectrum, with gradient influencing the relation between avulsion frequency and sediment supply (Ashworth et al., 2004).

4.2 Aggradation rate
Using experiments, numerical modelling and field evidence, Jerolmack and Mohrig (2007) showed that avulsion frequency in depositional rivers relates to the aggradation rate in the channel:

$$f_A = \frac{v_An}{\bar{h}}$$

(1)

where $f_A$ = avulsion frequency, $v_A$ = aggradation rate, $N$ = number of active channels, and $\bar{h}$ = the mean depth of channels. Using equation (1), they found close agreement between predicted and observed avulsion frequencies ($R^2 = 0.85$).

Reitz et al. (2010) added fan radius to this relation, making it more applicable to alluvial fans:

$$T_A(t) = \frac{hBr(t)}{Q_s}$$

(2)

where $T_A$ = the avulsion timescale (average time between avulsions), $h$ = channel depth, $B$ = channel width, $r$ = fan radius at time ($t$), and $Q_s$ = bedload input rate. This relation incorporates their observation that as fans grow (increasing $r$), the time between avulsions increases. Van Dijk et al. (2009) also observed that back-filling time increased as their experimental fans grew.
4.3 Mechanisms of back-filling
Recent experimental studies have examined channel back-filling on fans and fan-deltas (Reitz and Jerolmack, 2012; Van Dijk et al., 2009; 2012). Van Dijk et al. (2009; 2012) found that back-filling was initiated when a fan-front depositional lobe transformed into a mid-channel bar, which forced flow bifurcation. Reitz et al. (2010) suggested that a decreased slope at the fan-front was sufficient to initiate the process, and argued that presence of a mid-channel bar was unnecessary.

Reitz and Jerolmack (2012) proposed a further explanation for back-filling. They argued that the critical shear stress at which grains are entrained is greater than that at which they are deposited (the “distrainment” shear stress). They thus suggested that fans adjust to two “equilibrium” slopes, corresponding to the entrainment and distrainment stresses. They argued that back-filling was a form of self-adjustment to fill the “wedge” between these two slopes (Figure 3).

Figure 3: The avulsion cycle according to Reitz and Jerolmack (2012). Aggradation to fill the “wedge” between entrainment and distrainment slopes is shown in the inset fan profile diagrams.

4.4 Pre-existing fan topography
Aside from the channel itself, the morphology of the fan as a whole also influences avulsion – both the occurrence probability, and the path that avulsion takes. For instance, Jones and Schumm (1999) suggested that for avulsion to occur, the slope of the potential avulsion pathway must exceed that of the pre-avulsion channel. In addition, existing depressions on the fan surface act as attractors or conduits for avulsion – so much so that the erosion of a completely new channel by avulsion may be rare. For example, Reitz et al. (2010) observed that the channel in their experiments avulsed between an “active channel set” which acted as flow attractors. In the field, these depressions can include abandoned channels (Mohrig et al., 2000; Reitz and Jerolmack, 2012; Reitz et al., 2010; Sinha, 2009; Sinha et al., 2013), smaller channels which drain the fan surface but do not receive flow from its feeder catchment (Field, 2001) or even hippopotamus trails (McCarthy et al., 1992). The tendency to fill existing depressions on the fan has also been noted on debris fans (Pederson et al., 2015). Although avulsion on fans is a stochastic process at longer timescales, this apparent preference for pre-existing channels or depressions makes predicting avulsion pathways less difficult (Field, 2001; Pederson et al., 2015).
5. Avulsion on alluvial fans in British Columbia
The published literature on stream-flow dominated fans in British Columbia and Alberta has tended to focus on their long-term evolution, rather than the dynamics of contemporary avulsion. In particular, the stratigraphy and morphology of paraglacial fans have been rigorously investigated by Church and Ryder (1972) and Ryder (1971a, 1971b), and more recently by Ékes and Friele (2003) and Ékes and Hickin (2001). Active, contemporary processes on an alluvial fan in BC were studied by Goedhart and Smith (1998), who examined rates of aggradation and progradation during high flows. However, for geohazards on fans in BC and Alberta, it is perhaps more important to consider flows with higher sediment:water ratios, such as debris floods or flows. Fans affected by these processes have been studied in great detail, for instance by Jackson et al. (1987), Jakob and Friele (2010), Jakob and Hungr (2005, and papers therein), Kellerhals and Church (1990), and Wilford et al. (2004; 2005).

Predicting avulsion during stream floods on alluvial fans in BC may be a straightforward exercise, if the channel capacity, flood size and fan topography are known. However, as with all fans, the long-term frequency of avulsions on fully alluvial fans in BC likely depends on some combination of the channel size, long-term sediment supply rate, and aggradation rate, as well as the frequency of sediment-mobilising events. Our theoretical understandings of avulsion on fluvial fans are based on experiments with constant flow and sediment feed rates, and from field studies in arid regions. A better understanding of fluvial fans in humid regions such as BC could be gained from experiments with pulsed inputs of sediment and water.

6. Conclusion
Experiments have demonstrated the importance of internal feedbacks in driving avulsion on alluvial fans. When combined with the complexity of the real world, where environmental conditions are variable in time and space, predicting avulsion and linking cause and effect become difficult.

The processes driving avulsion on alluvial fans can be divided into “setup” and “trigger” processes. A trigger is usually a flood of moderate-to-large magnitude, but the avulsion setup has many influences. These include sediment supply and in-channel aggradation rate, which precondition the channel for avulsion by gradual filling with sediment.

For avulsion to occur, the potential avulsion pathway must usually be steeper than the existing channel. Pre-existing fan morphology thus influences the avulsion threshold, and is also important in directing the avulsion pathway, as avulsion often (re)occupies existing depressions on the fan.

In BC and Alberta, the study of fans has tended to focus on paraglacial fan evolution, or on the influence of debris floods or flows. These are a major influence on fans in high-relief terrain.

Many questions remain unanswered in the study of avulsion on fans. One problem that has not been well addressed is that of how avulsion occurrence is altered by human landscape modification. Studies have hinted at the role of landscape change in fan evolution, sediment transfer and avulsion occurrence (e.g. Aslan et al., 2005; Harvey, 1978; Schick et al., 1999). Nevertheless, this problem has not been given major consideration. One exception was the work of Heyvaert and Walstra (2016), who used a millennial scale archaeological record to examine how engineering works influenced the avulsion process at all stages of the avulsion cycle. Aside from this, studies of avulsion on fans have not focussed on how human landscape modification alters avulsion probability. As population pressures on fans increase, it becomes ever more crucial to understand the feedbacks between settlement intensity and avulsion probability.
Reference list


