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Making sense of avulsions on debris-flow fans

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Abstract

Avulsions remain a critical but understudied aspect of debris-flow fans and flow hazard. A substantial body of work on fluvial systems provides a conceptual framework for understanding avulsions, but equivalent research on debris-flow systems has lagged behind. A small but growing set of field examples and analogue experiments shows that many, but not all, avulsions on debris-flow fans follow a relatively predictable 'avulsion cycle' that consists of (1) deposition of debris-flow material in the active channel, (2) backstepping of deposition toward the fan apex in one or more small- to medium-sized surges or flows, and (3) avulsion during a subsequent larger surge or flow that leaves the channel and establishes a new pathway down the fan. Debris flows tend to occupy persistent pathways on the time scale of individual flows, but over longer time scales (perhaps greater than ~5-20 flows, based on very limited data) flows tend to avulse to fill topographic lows, leading to compensational behavior. Avulsions may be encouraged by sequences of small- to medium-sized flows followed by a large flow, and discouraged by sequences of large flows in succession, although this idea remains speculative and needs to be tested. Avulsion frequency is important for understanding flow hazard but is poorly constrained, and cannot yet be predicted as a function of either flow or catchment characteristics. The advent of new, high-resolution topographic data from fan surfaces, coupled with methods to estimate the timing and abandonment of deposition on a wide range of fans, should allow us to begin to make some initial estimates of avulsion frequency and to understand the key controls on the timing and pattern of avulsions.

Keywords: debris flows; fans; avulsions; avulsion frequency; hazard

1. Introduction

Debris-flow fans are semi-conical landforms that grow by the deposition of sediment in repeated flows from a mountain catchment. They are ubiquitous in high-relief areas around the world, and because of their relatively low surface slopes they are commonly used for settlement, agriculture, or other human activities. The construction of a debris-flow fan, however, requires that the locus of deposition must shift over time in order to fill the available accommodation. These episodic shifts in the position of the active channel are called avulsions.

Avulsions are critical events in the evolution of a debris-flow fan, and are important for several reasons. First, they control how sediment is distributed across the fan surface. Switching of the active channel between different pathways creates a small number of distinct sectors on the fan surface (Fig. 1). Each of these sectors records debris-flow activity during a particular period of time and over a number of flows (e.g., Schumm et al., 1987; Duehnforth et al., 2007; Schuerch et al., 2016). The sectors thus serve as an archive of past flow size and behavior, and potentially of the environmental conditions under which the flows occurred (d'Arcy et al., 2017). The intervals between avulsions set the period of time recorded by each sector, which can be as long as tens of thousands of years (e.g., Whipple and Dunne, 1992; Duehnforth et al., 2007; 2017).

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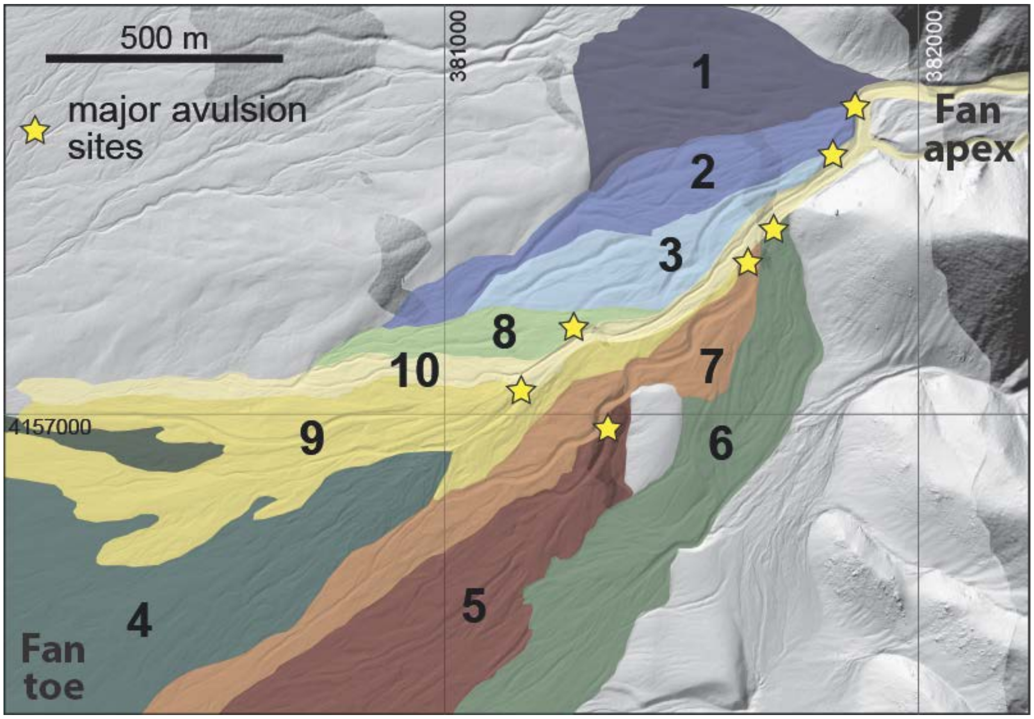

Fig. 1. Sectors on the Straight Canyon debris-flow fan, Chalfant Valley, California, USA, labelled from 1 (oldest) to 10 (youngest, the active channel). Flows travel from right to left across the fan. Stars show locations of major avulsions between sectors.

Second, the frequency of avulsions also determines the persistence of transport pathways (Jerolmack and Paola, 2007; Straub et al., 2009) and thus the architecture of the developing fan stratigraphy (Pederson et al., 2015). Finally, avulsions are also a key determinant of debris-flow hazard. Debris flows that leave the main channel pose the greatest threat to people and infrastructure, because mitigation measures such as check dams are usually applied only to the presently-active channel. Any migration of debris-flow activity outside of the main channel will thus bypass those mitigation measures and threaten other parts of the fan surface.

Despite this importance, avulsions on debris-flow fans have received little research attention. There are some documented examples in the literature, but very few systematic studies of avulsion location, trigger, mechanism, or frequency. This may in part be due to the long time periods between flows in many settings, which make direct observations of avulsions very rare (de Haas et al., 2018a). In addition, there are few debris-flow fans worldwide where debris-flow deposition in space and time has been monitored (e.g., Suwa and Okuda, 1983; Wasklewicz and Scheinert, 2016; Imaizumi et al., 2016) or reconstructed (e.g., Stoffel et al., 2008; Schuerch et al., 2016).

Here, we draw together findings from recent work on debris-flow avulsions and identify some key research priorities that must be tackled in order to understand the full role of avulsions in debris-flow hazard and fan development. For a wider review of debris-flow avulsions, we refer interested readers to de Haas et al. (2018a).

2. Fluvial context

Avulsions have long been recognised as a key element in fan development, irrespective of the sediment transport process. Dutton (1880) wrote eloquently about avulsions in describing the deposition of alluvial sediments at the 'gate' or mouth of a mountain catchment:

"When the stream is progressively building up its bed outside of the gate, it is obvious that it cannot long occupy one position; for if it persisted in running for a very long time in one place it would begin to build an embankment. Its position soon becomes unstable, and the slightest cause will divert it to a new bed which it builds up in turn, and which in turn becomes unstable and is also abandoned. The frequent repetition of these shiftings causes the course of the stream to vibrate radially around the gate as a center, and in the lapse of ages it builds up a half-cone, the apex of which is at the gate. The vibration is not regular, but vacillating, like a needle in a magnetic storm; but in the long run, and after very many shiftings, the stream will have swept over a whole semicircle with approximately equal and uniform results." (Dutton, 1880, pp. 220-221)

Much of our understanding of avulsions has been derived through observations of fluvial systems, and it is instructive to review some of that work here. Mohrig et al. (2000) showed that avulsions in ancient river deposits were linked to the aggradation of the river system by approximately one channel depth above the surrounding floodplain. We can define an avulsion frequency f_A as the rate of avulsion per unit time; Jerolmack and Mohrig (2007) argued that f_A should scale with mean channel depth $\bar{h}$, sediment aggradation rate v_A, and the number of active channels N as:

$$f_A = \frac{v_A N}{\bar{h}} \tag{1}$$

Reitz and Jerolmack (2012) proposed an alternative approach to estimate f_A based on channel geometry and the sediment supply rate, building on earlier work by Bryant et al. (1995):

$$f_A = \frac{Q_S}{\left[hBr(t) + \frac{\theta}{6}\sum \Delta y r^2(t)\right]} \tag{2}$$

where Q_s is the sediment supply rate, B is the channel width, $r(t)$ is the fan radius as a function of time, θ is the width of a channel lobe, and ΣΔy is the total vertical aggradation at the fan apex since a fan sector was last active.

Studies of natural and laboratory fluvial fan systems have documented the sequence of events in a typical 'avulsion cycle' (e.g., Schumm, 1987; Hoyal and Sheets, 2009; Reitz and Jerolmack, 2012; Ganti et al., 2016): an upstream-propagating wave of in-channel deposition and backfilling, followed by overbank flooding and a 'searching phase' during which several new channel pathways may be active, followed by concentration of flow into a new channel. Jerolmack and Paola (2007) argued that avulsions are steered by the presence of abandoned channels on the fan surface, leading to persistent re-occupation of a small number of sediment transport pathways. Straub et al. (2009) termed such behavior 'persistent' or 'anti-compensational', in contrast to 'compensational' behavior in which the channel avulses frequently to fill the topographically-lowest part of the fan surface.

While these studies provide a useful framework and show how avulsion frequency might scale with different measures of a sedimentary system, it is not clear how applicable they are to debris-flow fans. Field observations show that channel beds on debris-flow fans can be super-elevated by 2-5 channel depths or more above the surrounding fan surface (de Haas et al., 2019), so direct application of equation (1) may be limited. The episodic nature of debris flows and the capacity for flows to both erode and deposit sediment on a fan surface (e.g., Schuerch et al., 2011) complicate the definition of a sediment aggradation rate except over long time periods. For the moment, therefore, an expression for avulsion frequency f_A that is relevant for debris-flow fans remains a research priority.

3. Field observations

Field observations of avulsions have tended to focus on individual events, such as the major avulsion that occurred in 1984 on the Dolomite Canyon fan, California, USA, as documented by Blair and McPherson (1998). There, the initial flow surges formed a complex of levee and lobe deposits along the active channel pathway. The boulder-rich front of a large subsequent surge then blocked the channel near the fan apex and diverted the flow by an angle of about 70° into a new pathway.

To identify some common elements of debris-flow avulsions, de Haas et al. (2018a) assembled observations from 16 fans worldwide for which the spatio-temporal evolution of debris-flow activity could be determined. They noted that avulsions often, but not always, occurred in response to the deposition of debris-flow lobes that formed sediment 'plugs' (Fig. 2) within the active channel (e.g., Whipple and Dunne, 1992). These avulsions were often preceded by a sequence of small- to medium-size flows, and were most likely to occur when plugs were deposited in locations from which alternative pathways could be easily accessed by future flows. Plug formation was more likely in smaller flows or those with limited mobility. This overall pattern mimics in some way the avulsion cycle observed on fluvial fans – in particular, the role of small flows in setting the conditions for a subsequent avulsion, as argued by Field (2001) – although the processes involved in the individual phases are quite distinct.

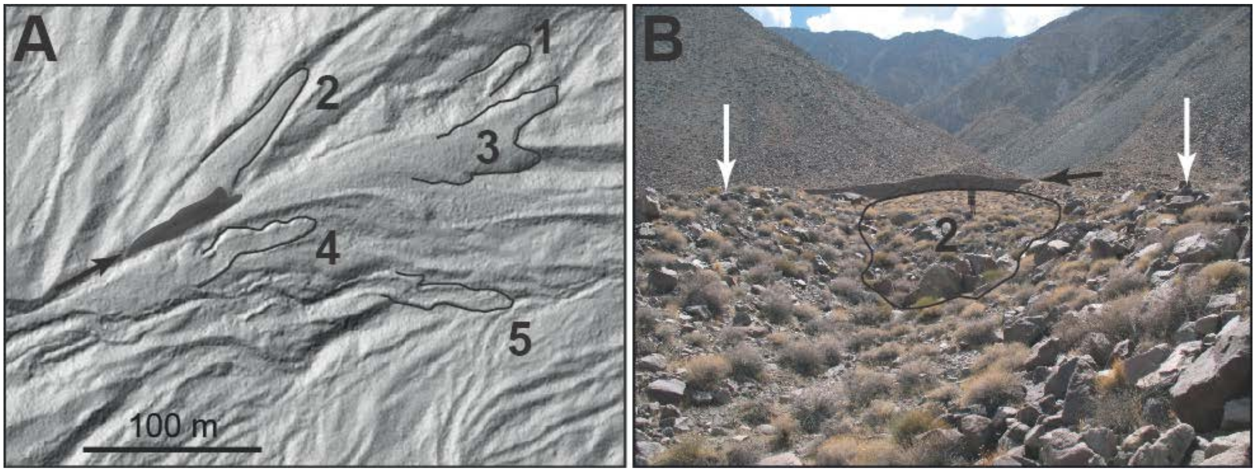

Fig. 2. (A) Shaded-relief image of the proximal part of a small debris-flow fan in Saline Valley, California, USA, showing a sequence of individual debris-flow lobes numbered 1-5 from oldest to youngest. Relative ages are based on cross-cutting relationships. Dark grey shaded area show left-lateral levee deposited after abandonment of lobe 2; black arrow shows flow direction. Image derived from Lidar topographic data with 0.5 m cell size. (B) Field photograph of lobe 2 from panel (A), outlined in black. Flow was toward the camera; note the figure on the lobe for scale. White arrows indicate the crests of the channel-margin levees. This lobe filled and blocked the active channel, forcing an avulsion to the east; a subsequent flow has deposited a lateral levee across the head of the channel (highlighted in dark grey), forcing its abandonment. Black arrow shows flow direction during subsequent levee deposition, as in panel (A).

De Haas et al. (2018a) noted that, unlike on fluvial fans (e.g., Ganti et al., 2016), very large flows (that is, those in the tail of the volume distribution) can have highly variable roles in avulsions. Large debris flows can spill out of the active channel and excavate a new channel or re-occupy an older abandoned channel. Sequences of large flows, however, may be more likely to erode the existing channel, enlarging it and thus making avulsion less likely, especially if the rate of bed entrainment depends on some measure of boundary shear stress (Schuerch et al., 2011; Iverson, 2012; Iverson and Ouyang, 2015). Large flows can also split among multiple channels, depositing material over a large area of the fan surface and increasing the likelihood of future avulsion (de Haas et al., 2018a).

Over sequences of ~5-20 flows, de Haas et al. (2018a) showed that the locus of deposition often tends to shift toward the topographically lowest areas of the fan. This indicates that flow pathways can persist over short time scales of a few flows, but tend toward compensational behavior over longer time scales, as seen in other sedimentary systems (e.g., Straub et al., 2009; van Dijk et al., 2016). A tendency toward long-term compensational behavior was also observed by Pederson et al. (2015), who demonstrated that deposition on three well-exposed debris-flow fans was intermediate between random and fully compensated over sequences of 22-28 individual beds. They inferred that compensational behavior and more frequent avulsions were likely to be enhanced by thick, wide, coarse-grained flows with high clay contents, arguing that such flows can more easily fill topographic lows and form thick deposits that will steer subsequent flows toward other areas of the fan (e.g., Whipple and Dunne, 1992).

4. Analogue experiments

To explore the link between the distribution of flow sizes and avulsion behavior, de Haas et al. (2018b) ran a series of analogue debris-flow experiments in a small laboratory flume and tank. This work built on earlier experiments in the same flume by de Haas et al. (2016), who constructed a model fan with a sequence of 55 flows, each with a total flow mass of ~6.5 kg. De Haas et al. (2018b) ran two additional experiments under identical conditions; however, rather than keeping the flow mass constant, the mass of each flow was chosen from a steep- or shallow-tailed double Pareto mass distribution. The mass of each flow in the two additional experiments ranged up to ~13 kg, although the mean flow mass in all three experiments was the same. All flows had an identical grain-size mixture and a water content of 44% by volume (see de Haas et al., 2016, for materials and methodology).

All three experiments showed broadly similar avulsion cycles that consisted of channel establishment, backstepping of deposition toward the fan apex, a ‘searching phase’ during which deposition spread across the proximal fan, and avulsion toward a new topographically-favorable sector. Comparable behavior was observed in analogue experiments by Schumm et al. (1987). In detail, however, the different flow mass distributions led to markedly-different avulsion mechanisms. A uniform flow mass distribution led to regular avulsion cycles in which backstepping deposition proceeded from fan toe to apex before avulsion occurred. In contrast, a steep-tailed distribution, corresponding to a narrow range of flow masses, led to two additional avulsion mechanisms: large events that could overtop existing channels and occupy new pathways, and sequences of small flows that led to plugging of only the proximal part of the active channel. A shallow-tailed distribution, with a wide range of flow masses, also showed these additional avulsion mechanisms, although the more frequent large flows excavated the main channel and made avulsions less common.

While these results are based on a small number of experiments and do not consider other factors that may be important, such as variations in flow mobility due to grain size or water content, they suggest that sequences of several small- to medium-sized flows may be critical in forcing avulsion in a subsequent larger flow – as observed, for example, on the Kamikamihori fan in Japan (Suwa and Okuda, 1983). The experimental results also highlight a major difference between the fluvial avulsion cycle and that observed on debris-flow fans: backfilling and channel plugging need not proceed up the entire fan surface in order to force avulsion on debris-flow fans, as is often the case on fluvial fans, but can be limited to a key reach or even a single point. This makes debris-flow avulsions harder to anticipate than their fluvial counterparts, and calls for research on likely avulsion locations.

5. Research priorities

In this final section, we summarise some of the key research priorities that would help to develop a more complete picture of avulsion.

5.1. Avulsion mechanisms and triggers

The avulsion cycle model outlined above predicts that avulsions should be enhanced by particular sequences of flow volumes – especially those in which a series of small- to medium-sized flows that partly or fully block the channel are followed by a large flow that triggers avulsion. As estimates of debris-flow volume are accumulated at more and more observation stations (e.g., McArdell et al., 2007), it should be possible to begin to relate the sequencing of flow volumes to the temporal evolution of bed elevation in different settings. It would also be useful to look for evidence of 'pre-conditioning' of an active channel for avulsion – e.g., via channel blockage in key locations on a fan, perhaps where channel incision into the fan surface is minimal and where there are abandoned channels that could form new flow pathways after an avulsion.

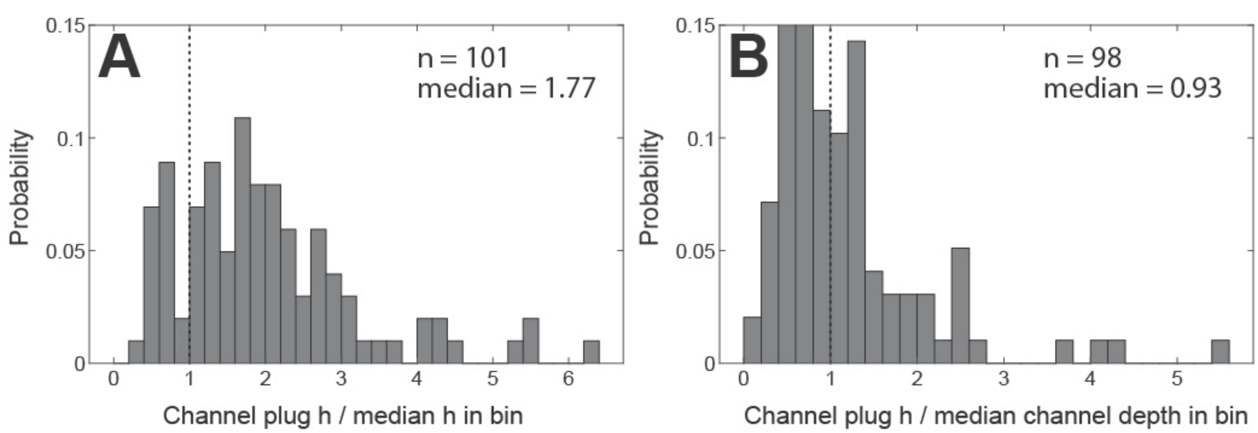

Fig. 3. Characteristics of debris-flow depositional lobes that form channel plugs on fans in Saline Valley. (A) Histogram of channel plug thickness. Values are binned at 50 m radial distance intervals from the fan apex and normalized by median lobe thickness within each bin. Most channel plugs that have triggered avulsion are thicker than the median lobe within that distance bin. (B) Histogram of channel plug thickness. Values are normalized by median channel depth within the same 50 m bins. Note similarity between plug thickness and median channel depth.

Some additional understanding of the formation of channel plugs can be gained by examining the characteristics of flow deposits that have triggered avulsions in the past. Measurements of channel depths and debris-flow depositional lobe thicknesses on fans in Saline Valley, California, USA (Fig. 2) from high-resolution Lidar topography (de Haas et al., 2019) show that depositional lobes that have plugged channels and triggered avulsions tend to be substantially thicker than the median lobe thickness at the same radial position on the fan (Fig. 3A), and to have thicknesses that are comparable to the median channel depth at the same radial position (Fig. 3B). While perhaps not surprising, this result confirms that plugs must fill a substantial portion of the available channel in order to force avulsion, and that channel plugging, rather than aggradation above the floodplain (e.g., Mohrig et al., 2000), is the key avulsion mechanism at this site. Avulsions can still be forced by plugs which are thinner than the median lobe thickness (Fig. 3A) or channel depth (Fig. 3B), but they are the exception. Similar measurements from other fan settings would be helpful in elucidating the sequence of events involved in channel plugging and avulsion.

5.2. Avulsion size and location

The impact of an avulsion on a fan surface depends on three factors: the size of the flow, the radial position at which the avulsion occurs, and the 'opening angle' between the old and new flow pathways. One reasonable measure of avulsion size is the incremental area of fan surface that is inundated after the avulsion, such that full resurfacing of the fan will occur once those incremental areas sum to the total fan area (e.g., Cazanacli et al., 2002). This measure, however, ignores the fact that a large opening angle can pose a hazard to infrastructure that is far from the old pathway, especially if mitigation measures are concentrated close to the active channel. Thus, an alternative measure of avulsion size M_a could be the product of the opening angle D_{az}, normalized by the total angle described by the fan, and the radial distance of the avulsion site from the fan toe D_r, normalized by the fan length (Fig. 4). M_a thus varies between 0 (no avulsion) and 1 (an avulsion at the apex from one fan margin to the other), and provides a way of comparing the potential impacts of avulsions that occur at different locations on the fan.

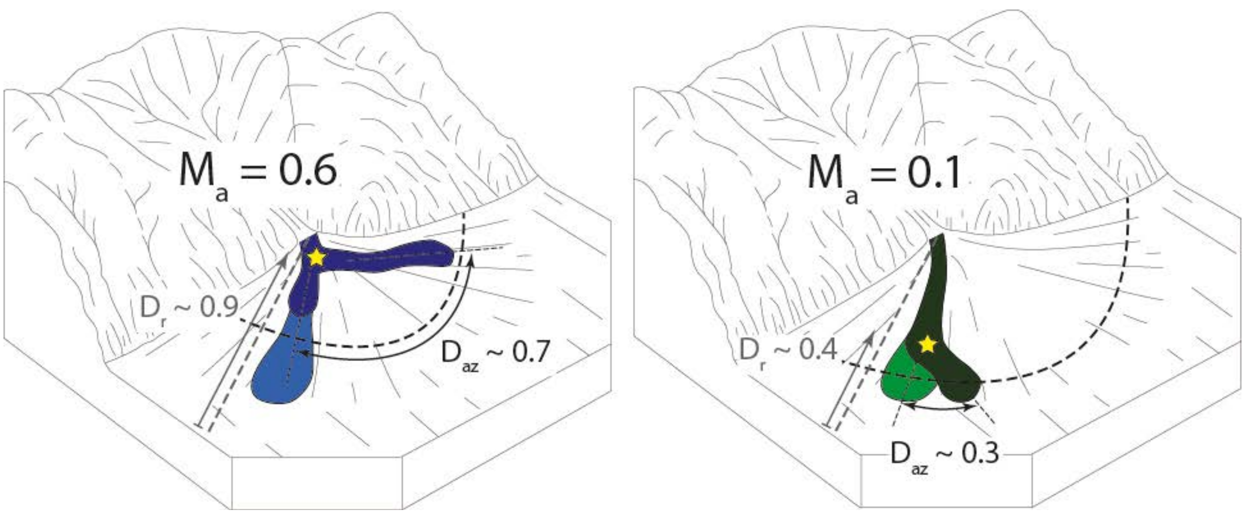

Fig. 4. Schematic of avulsion size M_a as a product of the normalized opening angle D_{az} and the normalized radial position D_r.

Jerolmack and Paola (2007) showed that avulsion sizes in their experiments (measured in terms of the length of new channel created) followed an exponential distribution. They demonstrated that there was no binary distinction between 'nodal' avulsions that occur at the fan apex and 'local' avulsions that occur elsewhere; instead, the former are simply less frequent. Field observations by de Haas et al. (2018a) tend to support that continuum, with avulsions possible at all radial positions on a fan surface. Field observations by Pederson et al. (2015) and experimental work by de Haas et al. (2018b) both suggest, however, that flows become more compensational, and avulsions thus somewhat more likely, on the distal parts of the fan surface – perhaps driven by down-fan decreases in channel depth that outweigh down-fan decreases in lobe thickness (Whipple and Dunne, 1992). It may thus be possible to identify avulsion 'hotspots' by comparing the thickness of typical debris-flow depositional lobes with typical channel depths; as both of these quantities vary down-fan, avulsions should be more common in areas where lobes can more easily fill and block the channel network. These observations also suggest that avulsions with high M_a – those that occur near the apex and have wide opening angles – should be comparatively rare events.

5.3. Avulsion frequency

We currently have no capacity to predict the occurrence or frequency of avulsions on debris-flow fans, meaning that our understanding of avulsion occurrence is almost entirely reactive. A major research priority is therefore to compile sufficient information on avulsion occurrence and timing to enable first-order comparison with channel and flow characteristics, sediment supply, and fan climatic and tectonic setting. De Haas et al. (2018a) reviewed the available data on historically-active debris-flow fans, and showed that documented avulsions occurred approximately every 3-8 flows. It is worth bearing in mind that those fans were specifically studied because of their frequent flow activity, and they are not necessarily representative of avulsion frequency on less-active fans.

Over the longer term, fans show evidence of switching between different sectors on a range of time scales: for example, sectors on the Illgraben fan in Switzerland are typically active for ~10^2 yr (Schuerch et al., 2016), but sectors on fans in Owens Valley, California, may be active for ~10^3-10^4 yr (Duehnforth et al., 2007; Le et al., 2007; d'Arcy et al., 2015). There are still relatively few well-dated fan surfaces worldwide for which the timing of sector activity and abandonment can be estimated. The explosion in the practicability of surface dating by analysis of *in-situ* cosmogenic radionuclides over the last 20 years, however, means that it is now more feasible than ever to generate quantitative fan-surface age estimates (e.g., Ivy-Ochs et al., 2013).

At the same time, fan sector identification is typically based on both quantitative and qualitative measures of fan surface topography, including such diverse observations as surface roughness at various scales, channel cross-cutting relationships, downlapping or onlapping relationships, relative weathering of surficial materials, soil development, and vegetation growth. Despite some efforts to quantify these measures (e.g., Frankel and Dolan, 2007), division of the fan surface into discrete sectors remains an uncertain and somewhat ambiguous exercise. Thus, while there is clearly a need for more fan-surface chronologies, we also suggest that attention should be given to the ways in which fan sectors are formed and abandoned, and the implications of these processes for the fidelity with which fan surfaces record avulsions.

5.4. Numerical modelling of avulsions

A promising approach for exploring the controls on avulsion frequency is through the numerical modelling of repeated flows and the concomitant evolution of fan surface topography. McDougall (2017), in a thorough review of landslide and debris-flow runout models, pointed out that predicting the occurrence, location, and impacts of avulsion in numerical flow models remains a major outstanding challenge. While existing flow models can simulate flow paths given some assumptions about initial flow volume and entrainment or deposition along the flow path (e.g., Frank et al., 2015), it is difficult even *a posteriori* to simulate major avulsions due to the need to model the dynamic feedbacks between entrainment or deposition, changes in the channel bed topography, flow volume, and flow behaviour. Recognition of other possible flow paths, for example due to the presence of abandoned channels on the fan surface, is not sufficient; avulsion into those paths requires filling of the active channel, routing of material down the new pathway, and sufficient excavation of the new channel to ensure that it is maintained in subsequent surges or flows. While runout models are typically used to reconstruct the pathways of individual debris flows, there has also been much less attention devoted to modelling the impact of series of flows on a fan surface; thus, the suggestion by de Haas et al. (2018b) that the sequence of flow sizes, as well as the sizes themselves, may be important for triggering avulsion remains untested by independent observations. Finally, fan surface models require sufficient field data to allow testing and evaluation – especially high-resolution topographic data that can resolve individual channels and lobes, as well as repeat imagery of fan surfaces that can be used to identify avulsion occurrence and magnitude. We therefore close by calling for concerted research effort toward the development of numerical approaches that can simulate avulsions and thus the spatial evolution of debris-flow hazard over sequences of multiple flows.

Acknowledgements

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