Avulsions and the spatio-temporal evolution of debris-flow fans

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Abstract

Debris flows are water-laden masses of sediment that move rapidly through channel networks and over alluvial fans, where they can devastate people and property. Episodic shifts in the position of a debris-flow channel, termed avulsions, are critical for debris-flow fan evolution and flow hazards, because avulsions distribute debris-flow deposits through space and time. However, both the mechanisms of flow avulsion, and their effects on the long-term evolution of debris-flow fans, are poorly understood. Here, we document and analyze the spatial and temporal patterns of debris-flow activity obtained by repeat topographic analyses, dendrogeomorphic and lichenometric reconstructions, and cosmogenic nuclide dating on 16 fans from Japan, USA, Switzerland, France, and Kyrgyzstan. Where possible, we analyze the observed spatio-temporal patterns of debris-flow activity in conjunction with high-resolution topographic data to identify the main controls on avulsion. We identify two main processes that control avulsions on debris-flow fans, operating over distinct time scales. First, during individual flows or flow surges, deposition of sediment plugs locally blocks channels and forces subsequent flows to avulse into alternative flow paths. Plug deposition is a stochastic process but depends in part on the sequence of flow volumes, the geometry of the channel, and the composition of the flows. Second, over time scales of tens of events, the average locus of debris-flow deposition gradually shifts towards the topographically lower parts of a fan, highlighting the importance of topographic compensation for fan evolution. Our documented debris-flow avulsions often, but not always, follow a pattern of channel plugging, backstepping of deposition toward the fan apex, avulsion and establishment of a new active channel. Large flows can have contrasting impacts, depending on whether or not they follow smaller flows that have deposited channel plugs. These results suggest that avulsions and spatio-temporal patterns of debris-flow fan formation strongly depend on the magnitude-frequency distribution and sequence of the flows feeding a fan. While individual avulsions are generally abrupt and difficult to predict, the presence of debris-flow plugs and patterns of backstepping may be useful as indicators of impending avulsions. Over longer time scales, the compensational tendency of flows to avulse into topographic depressions on the fan may also be used to identify sectors of the fan that are at risk of future inundation.

1 Introduction

Debris flows are common geomorphic processes in high-relief regions [e.g., *Takahashi*, 1978; *Iverson*, 1997; *De Haas et al.*, 2015b]. They are water-laden masses of soil and rock with volumetric sediment concentrations that generally exceed 40% [*Costa*, 1988; *Iverson*, 1997]. Deposition of sediment in repeated flows results in the formation of debris-flow fans, whose semi-conical shape is obtained by episodic avulsion of the active channel from a fixed fan apex [e.g., *De Haas et al.*, 2016]. Switching of the active channel between different transport pathways typically gives rise to a small number of distinct geomorphic sectors on the fan surface, each of which shows evidence for debris-flow activity during a particular period of time [e.g., *Dühnforth et al.*, 2007; *De Haas et al.*, 2014; *Schürch et al.*, 2016].

Debris-flow runout on fans can devastate both people and property [e.g., *Wieczorek et al.*, 2001; *Iverson*, 2014; *Dowling and Santi*, 2014]. The continued expansion of human population into mountainous regions has greatly increased the hazardous effects of debris flows [*Pederson et al.*, 2015], especially because the fans deposited by debris flows are preferred sites for settlements in mountainous areas [e.g., *Cavalli and Marchi*, 2008]. Moreover, ongoing climate change may increase the number and volume of debris flows, and thus hazards, due to increasing numbers of extreme precipitation events and permafrost degradation [e.g., *Jakob and Friele*, 2010; *Stoffel et al.*, 2014; *De Haas et al.*, 2015a]. It is thus critical to understand the processes that govern debris-flow deposition on fans, and especially the controls on flow avulsion between different fan sectors.

Avulsions distribute sediments and hazards through space and time on debris-flow fans. Debris flows that leave the main channel typically pose the largest threat to settlements and infrastructure on alluvial fans, as mitigation measures such as check dams and retention basins are often applied only to presently active channels. Yet, the mechanisms by which debris flows shift or avulse to occupy new flow paths on fans are poorly understood [e.g., *Pederson et al.*, 2015; *De Haas et al.*, 2016], in part because of a lack of field and experimental data on avulsions. Direct observation of the long-term evolution of natural debris-flow fans is inhibited by the small number of well-studied fans, long debris-flow return periods that typically range from a few to a few hundreds of years [e.g., *Van Steijn*, 1996], and the even larger return period of avulsions [e.g., *Zehfuss et al.*, 2001; *Dühnforth et al.*, 2007; *Stoffel et al.*, 2008]. Equifinality (the formation of similar landforms by different sets of processes), the limited exposure of the sedimentary record on most active debris-flow fans, and the lack of detailed dating methods beyond a few hundred years have further limited reconstructions of the evolution of natural debris-flow fans [*Ventra and Nichols*, 2014]. Physical scale experiments evaluating the spatio-temporal evolution of debris-flow fans are rare, and have only considered a few idealized scenarios [*Hooke*, 1967; *Schumm et al.*, 1987; *Zimmermann*, 1991; *De Haas et al.*, 2016]. Moreover, nearly all existing numerical debris-flow models have been limited to simulation of single debris-flow events [e.g., *Iverson*, 1997; *Pudasaini*, 2012; *Frank et al.*, 2015], and have not been used to study avulsions and fan evolution.

In contrast, the spatio-temporal formation of fluvial fans and deltas and their avulsion processes have been investigated in greater detail. Those systems appear to be governed by repeated sequences of avulsion, fan-head incision, and backfilling [e.g., *Schumm et al.*, 1987; *Bryant et al.*, 1995; *Whipple et al.*, 1998; *Van Dijk et al.*, 2009, 2012; *Clarke et al.*, 2010; *Reitz and Jerolmack*, 2012], which results in migration of the active locus of deposition in space and time and filling of the available accommodation space [*Straub et al.*, 2009]. Stratigraphic observations suggest that the mode of flow-path selection in both experimental and natural fan deltas can vary from random [*Chamberlin et al.*, 2016] to compensational, where channels commonly avulse to regional topographic depressions [*Straub et al.*, 2009; *Wang et al.*, 2011], to persistent, where channels occupy a small set of preferred pathways for extended periods of time before avulsing to a different fan sector [*Sheets et al.*, 2007; *Hajek et al.*, 2010; *Van Dijk et al.*, 2016]. Models and experiments suggest that these flow-path selection modes arise from the influence of the surface topography of the system [*Jerolmack and Paola*, 2007; *Reitz and Jerolmack*, 2012; *Edmonds et al.*, 2016], and that abandoned channels may act as preferential flow paths after avulsion [*Reitz et al.*, 2010]. Avulsion frequency in fluvial systems appears to scale with the time required to aggrade one channel depth above the floodplain [e.g., *Jerolmack and Mohrig*, 2007; *Carling et al.*, 2016], although channels may also avulse due to upstream-migrating waves of aggradation ('backfilling') that follow progradation [e.g., *Hoyal and Sheets*, 2009; *Reitz et al.*, 2010; *Van Dijk et al.*, 2012]. For a given channel depth, the avulsion timescale is then expected to scale with the depth divided by the rate of aggradation [*Jerolmack and Mohrig*, 2007].

Quasi-cyclic alternations of avulsion, channelization and backstepping of the active depocenter have been documented on small-scale experimental debris-flow fans by *Schumm et al.* [1987] and *De Haas et al.* [2016], and the spatio-temporal pattern of the locus of deposition on natural debris-flow fans may show similar patterns of backstepping and avulsion [e.g., *Suwa and Okuda*, 1983; *Dühnforth et al.*, 2007; *Schürch et al.*, 2016]. These observed similarities in the spatio-temporal development of debris-flow fans and fluvial fans and deltas suggest that debris-flow fan evolution may be governed by comparable forcings, despite their fundamentally different physical processes. There has been no systematic survey of field-scale avulsion behavior, however, so such comparisons remain tentative at best. While spatio-temporal patterns of deposition on a few debris-flow fans have been monitored [*Suwa and Okuda*, 1983; *Wasklewicz and Scheinert*, 2016; *Imaizumi et al.*, 2016] or reconstructed [e.g., *Helsen et al.*, 2002; *Dühnforth et al.*, 2008; *Stoffel et al.*, 2008; *Procter et al.*, 2012; *Zaginaev et al.*, 2016], the observed patterns have not been quantitatively compared to infer general trends. There has also been little consideration to date of flow routing on debris-flow fans. Preliminary analysis of three natural debris-flow fans by *Pederson et al.* [2015] shows that flow path selection on debris-flow fans can vary from random to highly compensational, depending on debris-flow size, composition and longitudinal position on the fan. Finally, the impact of the flow magnitude-frequency distribution on avulsion behavior remains unclear. For example, are avulsions typically triggered by large flows that are able to overtop the main channel, or are they caused by smaller flows that plug the main channel and trigger avulsion in subsequent events? Such an understanding would greatly aid our ability to anticipate and mitigate avulsion hazard.

In this paper, we aim to (1) identify generic spatio-temporal patterns of debris-flow fan evolution and by doing so (2) determine the processes controlling avulsions on debris-flow fans. We compile and analyze a dataset of 16 debris-flow fans for which the spatio-temporal depositional history has been directly observed or reconstructed over a sequence of flows. Moreover, where possible we evaluate the influence of fan surface topography (e.g., channel plugs, topographic depressions and abandoned channels) on debris-flow avulsion and flow routing.

Here, we define a channel plug as a depositional feature that locally blocks the channel or reduces channel capacity, and causes subsequent flows to either avulse or deposit directly upstream of the depositional feature. Depositional features forming channel plugs may include debris-flow snouts, large boulders and log-jams.

This paper is structured as follows. We first describe the study sites, observation and reconstruction methods, and spatio-temporal pattern extraction and analysis methods. Then we describe the observed and reconstructed spatio-temporal patterns of debris-flow activity of the studied fans. Finally, we discuss the generic processes of avulsion on debris-flow fans, the role of flow size and sequence in avulsion, provide tentative estimates of avulsion frequency, compare avulsion and fan evolution on natural debris-flow fans to experimental and fluvial fans, and provide implications for debris-flow hazard mitigation and future research directions.

2 Materials and methods

2.1 Study sites

Our dataset contains 16 debris-flow fans from various mountain ranges in the USA, Japan, Switzerland, France, and Kyrgyzstan and covers a broad range of lithologies, fan sizes and fan slopes (Fig. 1, Table 1). This dataset contains all examples that we know of that are of sufficient detail and quality to investigate the avulsion mechanism and spatio-temporal development of fan deposition.

2.2 Observation and reconstruction methods

The study sites can be divided into three categories: (1) fans where topographic measurements have been performed repeatedly to measure the surface changes after one or a few debris flows; (2) reconstructions of the spatio-temporal patterns of deposition based on dendrogeomorphology or lichenometry; and (3) reconstructions of the time of activity of fan sectors (built by numerous debris flows) by dating of boulders with cosmogenic radionuclides.

Repeat topographic measurements resolve the distribution of debris-flow events in great detail, providing information on event volumes and the detailed controls on flow deposition. These measurements generally only cover a restricted amount of time (typically up to a few decades at most) and a small numbers of events [e.g., *Suwa et al.*, 2011; *Imaizumi et al.*, 2016; *Wasklewicz and Scheinert*, 2016]. A potential caveat is that only the net elevation change between successive surveys is captured, so that erosion and re-deposition as well as fluvial reworking may go undetected. Dendrogeomorphology and lichenometry enable reconstruction of individual flows up to a few centuries back in time with high temporal resolution (accuracy within a year for dendrogeomorphology and a few years for lichenometry) and reasonable spatial accuracy. Event volumes and thickness of deposits are often unknown, with the well-studied Ritigraben fan in the Swiss Alps as an exception [e.g., *Stoffel et al.*, 2008; *Stoffel*, 2010]. Reconstructions of the time of activity of fan sectors using cosmogenic nuclides do not resolve the evolution and avulsive behavior at the event scale, but they provide information on the patterns of avulsion and abandonment of entire fan sectors over time periods of hundreds to tens of thousands of years. As such, these reconstructions shed light on the long-term evolution of debris-flow fans, and help to pinpoint differences in avulsive behavior on large compared to small-sized fans.

On debris-flow fans where trees are abundant and of considerable age debris-flow activity can be reconstructed over multiple centuries by tree-ring analysis, sometimes down to intra-annual accuracy [e.g., *Stoffel and Beniston*, 2006; *Stoffel et al.*, 2008; *Stoffel and Bollschweiler*, 2009]. Although reconstructions of debris-flow activity via dendrogeomorphology have great potential for unraveling the spatio-temporal evolution of debris-flow fans the following pitfalls need to be taken into consideration when analyzing such data. Accuracy of reconstructions, especially of the spatial extent of events, does decrease with age as there is a decreasing amount of trees of sufficient age [e.g., *Stoffel et al.*, 2008]. The spatial extent of older events may not always be fully recognized as (parts of) the deposits of such events may be overridden or eroded by more recent activity. A smaller number of lobes and affected trees may thus not imply that these events were of smaller magnitude than more recent events [*Stoffel et al.*, 2008]. To be recognized in the tree-ring record, debris-flow events need to be of sufficient size to injure trees while small enough not to kill them [e.g., *Imaizumi et al.*, 2016]. The active parts of alluvial fans are often too geomorphologically active to allow the growth and survival of vegetation, and therefore events solely following the active channel may remain undetected in dendrogeomorphic reconstructions, unless they impact trees standing at the edge of the channel [*Arbellay et al.*, 2010]. Yet, events that remain in the main channel are not avulsive by default and therefore missing these events is not crucial for the analyses of the avulsion dynamics on debris-flow fans, although they may cause critical in-channel deposition causing avulsion of subsequent debris flows. Finally, as data is typically accurate within one year, one has to assume that all trees affected within a certain year belong to the same event, which in the majority of the cases is a valid assumption given the typical return period of debris flows [e.g., *Van Steijn*, 1996; *Schneuwly-Bollschweiler and Stoffel*, 2012].

In areas where trees are scarce, debris-flow deposits may be dated by lichenometry [e.g., *André*, 1990; *Helsen et al.*, 2002]. Such reconstruction may go back to over a century, but there is an incubation time before lichens start growing on rocks (approximately 10-20 yr). Accuracy of the method typically falls within a few years, which is generally sufficient for resolving the relative chronology of events [e.g,. *Blijenberg*, 1998]. Lichenometry can only be applied on preserved debris-flow deposits, whereas tree rings may record former debris-flow activity where deposits are no longer surficially preserved.

The spatio-temporal patterns of activity of geomorphologically distinct fan sectors is typically done by combining relative chronology obtained by cross-cutting relationships with cosmogenic nuclide dating of boulders present on the surface of these lobes [*Dühnforth et al.*, 2007; *Schürch et al.*, 2016]. The reconstructed chronology gives a representation of where the main locus of deposition took place during certain time periods, but does not resolve activity on an event basis. However, it opens up the opportunity to study the development of relatively large fan systems over multiple tens of millennia of time. The ages of the fan sectors serve as indication of the age range during which these systems were active as it cannot be assumed that both the oldest and youngest boulder on a certain fan sector has been dated.

2.3 Spatio-temporal pattern extraction and analyses

For fans with successive topographic measurements (Table 1), we analyze the spatio-temporal patterns of debris-flow activity from digital elevation models (DEMs) of difference of successive topographic measurements. Fans where debris-flow activity has been reconstructed from dendrogeomorphology and lichenometry include more flows but with lower spatial accuracy. Therefore, for these fans we summarize the spatio-temporal patterns of deposition for each event by the azimuth of the flow and the runout distance from the fan apex per deposit lobe (Ritigraben, Chalance, TCP, TCP-N1, TdW, TGE/TGW) or per affected tree (Grosse Grabe, Birchbach, Bruchji, Aksay). We accomplish this by defining the fan apex location and determining the distance of the lobe or affected tree from this apex as well as the azimuth relative to the fan midline (Fig. 2). Many events include multiple lobe deposits or have affected multiple trees. To identify the general location of debris-flow activity and changes therein, we summarize the flow direction by a weighted average flow angle, where the weight assigned to a lobe or affected tree increases linearly with runout distance.

To resolve the topographically favorable flow direction down the fans, we determine the average slope from the apex to a fixed downslope distance on the fan at 1 degree flow azimuth intervals. We conduct this analysis across radial distances that are multiples of 100 m from the apex. We always calculate the average distance from the apex towards these distances (e.g., apex to 100 m downfan, apex to 200 m downfan, leading to a collapse of the gradient with increasing distance from the apex), as the strength of the topographic control on flow direction decreases with increasing distance from the fan apex.

3 Results

3.1 Topographic measurements of debris-flow fan evolution

3.1.1 Chalk Creek

The Chalk Creek fan originates from the Chalk Cliffs in the Sawatch Mountain Range of Colorado (Fig. 1a). The debris flows at the Chalk Cliffs are typically composed of multiple granular surges, dominantly composed of cobbles and boulders without visible interstitial fluid, separated by fluid-rich, inter-surge flows [*McCoy et al.*, 2010, 2011, 2012]. The primary fan is deeply incised and debris flows are routed towards the fan toe where a small secondary fan has developed at the confluence with the Chalk Creek River. The development of this secondary fan has been monitored by *Wasklewicz and Scheinert* [2016] on six occasions between May 2009 and 2011, during which multiple debris-flow events have occurred.

During the summer of 2009, debris-flow deposition was concentrated on the southern part of the embryonic Chalk Creek fan (Fig. 3a, supplementary movies S1-S2). A flow between September 2009 and June 2010 led to deposition and filling of the incised apex channel (Fig. 3b). A subsequent flow between June 2010 and July 2010, while largely contributing material to the southern portion of the fan, opened up a pathway to the northern part of the fan, occupying and depositing material along the margins of an abandoned channel (Fig. 3c). This newly formed northern pathway was re-activated to a larger extent during the next flow between July 2010 and August 2010 (Fig. 3d). The final observed flow, which occurred between August 2010 and July 2011, deposited more material on the northern than on the southern portion of the fan (Fig. 3e). During this event the formerly active southern channel became clogged with sediment. Since July 2011 debris-flow activity has focused on the northern part of the fan, as confirmed by a 2012 field visit and 2013 Google Earth imagery [*Wasklewicz and Scheinert*, 2016].

The initial shift of debris-flow activity from south to north was induced by overtopping of the shallow apex channel ($\sim$0.3 m), as a result of aggradation during the relatively small debris-flow event that occurred between September 2009 and June 2010, as well as by the relatively large size of the two subsequent debris flows (Fig. 3). After overtopping the apex channel, the flow was able to follow the steeper gradient of an older flow path down the fan (Fig. 4). Water-rich inter-surge flows likely initially excavated the new pathways, which were then enlarged by subsequent debris flows, finally resulting in a full northern avulsion. Observations also indicate that the inter-surge flows associated with the debris flow using the initial channel also erode these channels after the initial surge(s) moved through these channels. In short, while the initial avulsion on the Chalk Creek fan was triggered by a single event, a full switch to the topographically favorable northern pathway developed over multiple flows.

3.1.2 Ohya

The Ohya landslide, in the southern Japanese Alps, was initiated during an earthquake in A.D. 1707 [*Tsuchiya et al.*, 2010]. Unstable slope material has subsequently been supplied into the channels in the old landslide scar, which has led to the frequent occurrence of debris flows and formation of a debris-flow fan on top of the former landslide deposits (Figs 1b, 5, supplementary movies S3-S4) [*Imaizumi et al.*, 2016].

Both fully and partly saturated debris flows have been observed at the Ohya landslide. The former flows can be characterized as watery, mud-rich, flows with few cobbles and boulders, while the latter are water-poor flows that dominantly consist of cobbles and boulders [*Imaizumi et al.*, 2005, 2017; *Imaizumi and Tsuchiya*, 2008].

The elevation of the fan surface has been repeatedly measured via airborne LiDAR scanning in 2005, 2006, 2009, 2010, 2011, 2012 and 2013, highlighting changes in the pattern of debris-flow activity on the fan within these time intervals [*Imaizumi et al.*, 2016]. The elevation differences observed on the DEMs of difference are the result of 2 to 5 debris flows per year from 2005 to 2013 (Fig. 5). Flows during 2006-2009 and 2010-2011 transported approximately 2-3 times the volume transported during the other investigated periods. Real-time monitoring data show that the debris-flow events typically included a few to dozens of surges [*Imaizumi et al.*, 2016].

During the period 2005-2006, debris-flow activity focused in the main channel following the western margin of the fan (Fig. 5a). There was net deposition near the fan apex and on the distal parts of the fan, whereas considerable erosion took place midfan. In the period 2006-2009, the distal parts of the main channel experienced severe erosion by debris flows, with erosion depths >3 m (Fig. 5b). Midfan, the channel was plugged by at least 6 amalgamated debris-flow lobes, together accounting for up to 3 m of vertical aggradation. Upstream of this debris-flow plug, a new pathway was established along an abandoned channel along the center of the fan, and flows exploited this to deposit multiple debris-flow lobes on the distal parts of the fan. A secondary channel with a restricted length formed on the proximal-eastern margin of the fan. In the period 2009-2010 only minor debris flows affected the fan, depositing material in the main channel near the fan apex (Fig. 5c). The large volume of sediment deposited on the fan during 2010-2011 was concentrated on the mid-west of the fan, again forming a large plug consisting of numerous debris-flow lobes (Fig. 5d). These lobes were deposited progressively upstream behind the plug that had formed in the same area from 2006 to 2009, creating a backstepping of the depositional locus. The central and eastern channels were also reactivated, presumably after the formation of the large plug blocking the channel along the west of the fan. The central channel routed debris flows to the distal parts of the fan, and appears to have become plugged when backstepping of lobes above the large western plug reached, and blocked, the entrance to this channel. The eastern channel was slightly enlarged, mainly in length, between 2010 and 2011. Between 2011 and 2012, all flows followed the western pathway along the main channel, scouring through the large plug blocking the channel (Fig. 5e). This channel subsequently became plugged again in 2012-2013 by 3-4 debris-flow lobe deposits, forcing avulsion to the central and eastern channels (Fig. 5f). The entrance of the central channel, however, was thereafter plugged by $\sim$3 debris-flow lobes, presumably forcing flow towards the eastern channel and further enlarging it. Interestingly, in the period 2012-2013 activity was roughly split between the main, central, and eastern channels along the fan, in contrast to the period between 2005 and 2012 when most activity took place in the main channel.

The elevation data show that all avulsions coincided with significant channel bed aggradation slightly downstream of the avulsion location by debris-flow lobes, showing that avulsion occurred only after deposition of one or more channel plugs. Over a longer time period, the increasing activity on the central and eastern part of the fan compared to the main channel between 2005 and 2013 appears to be a result of fan topography. Whereas average slopes from the avulsion apex to the distal fan (Fig. 6c,d) have been steepest on the western side between 2005 and 2013, the steepest gradients on the proximal fan have shifted from west to east during the study period (Fig. 6a,b). By 2013 the steepest slopes on the proximal part of the fan were in the center, which is consistent with the location of the frequently reactivated central channel as well as with the apparent shift towards debris-flow activity on the central to eastern parts of the fan.

3.1.3 Kamikamihori

The Kamikamihori debris-flow fan is fed by the Kamikamihori gully that originates from Mount Yakedake in the northern Japanese Alps (Fig. 1c) [e.g., *Okuda et al.*, 1981; *Suwa and*

Okuda, 1983; *Suwa and Yamakoshi*, 1999; *Suwa et al.*, 2009]. In 1962, a phreatic eruption occurred from a new fissure in the headwaters of the gully, which resulted in a high debris-flow frequency in the decades after this eruption. A debris-flow observation station was installed in 1970 in the Kamikamihori Creek.

In general, storm runoff in the headwaters induces muddy hyperconcentrated stream flows, which turn into debris flows, comprising boulder-rich surge fronts, while flowing through the Kamikamihori gully [*Suwa*, 1988; *Suwa et al.*, 2009, 2011]. On the Kamikamihori fan two main types of deposits have been observed: (1) flows that come to rest on the proximal parts of the fan typically form thick deposits with open-work, boulder-rich, steep marginal slopes, while (2) deposits on the proximal part of the fan are flatter, without a marked snout and supported by a sandy matrix ['swollen' and 'flat' lobes in *Suwa and Okuda*, 1983, respectively].

The spatial extent of debris-flow deposits that formed on the Kamikamihori fan was mapped after each debris-flow event on the fan since 1978 (Fig. 7, supplementary movie S5). Evidence from depositional activity between 1970 and 1977 is only anecdotal [*Suwa and Okuda*, 1983; *Suwa and Yamakoshi*, 1999], mapped outlines of debris-flow activity between 1978 and 1997 stem from *Suwa and Okuda* [1983], *Suwa and Yamakoshi* [1999] and *Suwa et al.* [2009]. Mapped outlines after 1997 are newly presented here.

Debris-flow activity on the Kamikamihori fan between September 1970 and July 2005 focused within three pathways along the southern margin, center, and northern margin (Fig. 7, supplementary movie S5). In 1970 and 1971 debris-flow activity was focused in a channel along the southern margin [*Suwa and Okuda*, 1983]. The formation of a channel plug near the fan apex during a flow on 17 September 1972 induced an avulsion to an abandoned channel on the central part of the fan, with minor deposition of flow material on the northern part of the fan [*Suwa and Okuda*, 1983; *Suwa and Yamakoshi*, 1999]. Debris-flow activity remained focused in the central channel, with occasional overspills to the north, from 1972-1978 [*Suwa and Yamakoshi*, 1999].

Flows in August and September 1978 followed the central channel towards the distal parts of the fan, leaving a set of downlapping depositional lobes that progressively backstepped toward the apex by about 100 m (Fig. 7). Subsequently, the fan was affected by a very large debris flow that occurred in August 1979. This event avulsed northward just upstream of the downlapping debris-flow lobes formed in 1978, and formed a series of depositional lobes. The large 1979 debris flow initially reached the distal part of the fan, after which debris-flow lobes were backstepping for almost 250 m until a subsequent surge was forced out of the central channel approximately 300 m downstream of the fan apex resulting in an avulsion towards the northern margin of the fan where a large depositional lobe was formed. During the final phase a large and thick debris-flow deposit was formed in the central channel slightly upstream of the previous avulsion location blocking the entrance of the newly formed northern pathway. As a result, the next flow in September 1979 re-occupied the central channel towards the distal parts of the fan. The next debris-flow event (August 1980) had a restricted runout and formed a plug in the central channel near the fan apex. The following three debris-flow events, occurring on 5, 7 and 22 September 1983, then avulsed towards the southern channel forming debris-flow deposits near the fan toe. The event on July 1985 also followed the southern channel but deposited on the proximal part of the fan and plugged the active channel. The following three events (September 1985 - August 1995) were blocked by this deposit, leading to progressive backstepping of the depositional lobes up to the fan apex. Thus, by August 1995, both the proximal parts of the southern and central parts of the fan were blocked by a series of downlapping debris-flow lobes. This caused the next, relatively large debris flow in July 1997, to avulse and follow the northern margin of the fan. Between July 1997 and 2007 debris-flow activity has remained focused in this northern pathway.

The observed patterns of debris-flow deposition on the Kamikamihori fan follow a quasi-cyclic pattern of channel plugging, backstepping of deposition, and avulsion. Deposits in successive flows generally migrate up-fan until a debris flow occurs that is of sufficient size to leave the main channel and to carve a new channel or reoccupy an older channel further down the fan. Relatively large debris flows enlarge existing channels or cut new channels, whereas a succession of smaller and/or less mobile, coarse-grained, flows form channel plugs and force the debris-flow lobe termination point to migrate upwards along the channel [*Suwa and Okuda*, 1983; *Suwa et al.*, 2009; *Okano et al.*, 2012]. Avulsions are thus typically triggered by sequences of small flows that fill the channel, followed by large flows that avulse into a new pathway (Fig. 7).

3.2 Reconstructions based on dendrogeomorphology and lichenometry

3.2.1 Ritigraben

The Ritigraben fan is located on the eastern side of the Matter Valley in the Swiss Alps (Fig. 1d). Geomorphic mapping by *Stoffel et al.* [2005] and *Stoffel et al.* [2008] has led to identification of 769 features relating to past debris-flow activity, including 291 lobes, 465 levees, and 13 well-developed channels. Many of these debris-flow features have been dated using dendrogeomorphology by *Stoffel et al.* [2005] and *Stoffel et al.* [2008], and the flow volumes were estimated by *Stoffel* [2010] (Fig. 8, supplementary movie S6).

The spatio-temporal patterns of debris-flow activity on the Ritigraben fan since AD 1566 are summarized in Figure 8. Reconstructed debris-flow events sometimes followed a single channel but generally multiple channels on the fan surface were activated during the same event and multiple depositional lobes were formed. Reconstructed flows 1 to 19 (the period <1794-1922) predominantly affected the middle of the fan between flow angles of -10° to 20° (Fig. 8), although individual flows or surges were able to affect the entire fan. The main locus of deposition migrated northward during this time (towards positive flow angles in Fig. 8a). The debris flow of 1922, event 19 in Figure 8, was exceptionally large (Fig. 8b) [*Stoffel*, 2010] and led to deposition of large amounts of sediment in the central sector of the fan. In particular, a very large depositional lobe comprising boulders up to 3 m in diameter was formed slightly downstream of the fan apex [*Stoffel et al.*, 2008]. This lobe blocked the central sector of the fan for subsequent flows (Fig. 8a) and led to a lower gradient for the central sector (Fig. 8c). As a result, subsequent flows occupied flow paths on the sides of the fan to the north and south of the 1922 plug. Flows 20-22 followed the northern pathway, but flow 23 occupied the southern pathway. Subsequent flows alternated between the two pathways or employed both, although over time the southern pathway became predominant while the northern pathway closed off. This gradual shift appears to be facilitated by a gradient advantage on the southern pathway, which is presently on average 1-2° steeper than the northern part of the fan (Fig. 8c). Abandonment of the northern pathway occurred through backstepping of deposition in successive flows and emplacement of multiple lobes near the proximal entrance to the pathway (supplementary movie S6).

The shifts of the locus of deposition on the Ritigraben fan show that avulsion can be a gradual process, typically taking multiple flows to complete. Although channel shift angles on the Ritigraben fan between successive events may be large, likely as a result of local steering by microtopography, local channel plugging, and overtopping, average shifts in the locus of deposition are gradual and appear to be driven by large-scale topographic compensation. The 1922 debris flow shows how large flows can deposit multiple lobes or plugs that affect the flow direction of numerous subsequent flows.

3.2.2 Bruchji

The Bruchji debris-flow fan is located north-northeast of the village of Blatten in the Swiss Alps (Fig. 1g). The spatio-temporal patterns of debris-flow activity on the Bruchji fan have been inferred from the distribution of affected trees by *Bollschweiler et al.* [2008] (supplementary movie S7). The reconstructed debris-flow events often affected relatively large fractions of the fan surface, occupying multiple channels on the fan surface [*Bollschweiler et al.*, 2007]. The events of 1935, 1941, 1943, 1959, and 1962 (events 19, 21, 22, 29, and 30 in Figure 9, respectively) were probably particularly large events as they affected trees all over the fan [*Bollschweiler et al.*, 2007]. *Bollschweiler et al.* [2007] suggested that most of the events recorded on the fan surface were debris flows, although some may have been hyperconcentrated flows, and we do not distinguish between those flow types here.

Debris-flow activity on the Bruchji fan took place south of the present main channel between 1867 and 1947 (events 1-24 in Fig. 9a), although there was a gradual shift toward the north. Flow 25 in 1950 opened a new pathway to the north of the main channel, and flow activity began to occur regularly on the northern part of the fan. The gradual northward shift has probably been driven by a gradient advantage on the proximal part of the fan, where fan slopes are approximately 1-2° higher on the northern flank as compared to the area occupied during flows 1-24 (Fig. 9b).

As a result of the age of trees sampled, events occurring before 1935 (events 1-18) cannot be identified on the northern part of the fan. *Bollschweiler et al.* [2007] suggested, however, that events affecting the northern part of the fan must have been very unusual before 1935, based on aerial photographs and on building activity on this part of the fan prior to 1935. Beginning in the late 1970s, various protection measures were undertaken to prevent debris flows from reaching the southern part of the fan. These measures have potentially affected events 37-41, explaining the decline of affected trees on the southern part of the fan since event 37. Still, the data show that debris-flow activity was already increasingly focused on the northern parts of the fan before event 37 and that partial abandonment of the southern parts had already begun.

There does not seem to be a correlation between the initiation of debris-flow activity on the north of the fan in 1950 (event 25) and the large events identified by *Bollschweiler et al.* [2007], suggesting that this shift was unrelated to these events. The event of 1947 (event 24), just prior to the northward avulsion, did not affect a great number of trees on the fan surface.

3.2.3 Grosse Grabe

The Grosse Grabe debris-flow fan is located on the west-facing slope of the Matter Valley (Swiss Alps) (Fig. 1e). *Bollschweiler et al.* [2008] inferred the spatio-temporal patterns of debris-flow activity for the proximal and middle parts of this fan, based on the distribution of affected trees (supplementary movie S8). They did not analyse the distal parts of the Grosse Grabe fan because of human disturbance of the fan surface. The middle part of the Grosse Grabe fan is largely built up by debris-flow channels while lobate deposits are relatively rare because of the steep fan gradient, in contrast to the Ritigraben and Bruchji fans whereon lobes are more abundant [*Bollschweiler et al.*, 2008].

The majority of the 35 reconstructed events since 1782 on the Grosse Grabe have affected the northern part of the fan (Fig. 10a). Moreover, the main locus of activity does not seem to have substantially changed over this period. A few debris-flow events affected both the southern and northern sides of the fan, whereas none have affected the southern side only. The average fan slopes on the Grosse Grabe are remarkably similar on all radial angles, such that no side is topographically preferred over the other (Fig. 10b). The long-term main activity on the northern side of the fan may be caused by the large incised present-day active channel on this side ($\sim$10 m deep; Grosse Grabe means large channel in Swiss, and the deeply-incised channel is already present on topographic maps from the 1890s). The majority of the debris flows seem to have been routed through this channel, and have only spilled out onto the fan at a sharp outer bend in the midfan, resulting in deposition that is largely restricted to the northern side of the fan.

The last 15 reconstructed flows all affected the northern part of the fan (since 1941). This may imply that the present-day, extremely deep, apex channel may have been this deeply incised since then, so that no debris-flow were able to overtop the channel near the apex.

3.2.4 Birchbach

The Birchbach debris-flow fan is located on the west-facing slopes of the Matter Valley (Swiss Alps) (Fig. 1f). The spatio-temporal patterns of debris-flow activity on this fan have been inferred from the distribution of affected trees by [*Bollschweiler and Stoffel*, 2010] (supplementary movie S9). Only the central sector of the fan is forested, and thus past events have only been reconstructed for this sector [*Bollschweiler and Stoffel*, 2010].

Flow activity on the Birchbach fan took place both north and south of the main channel between 1755 and 2000 (Fig. 11a). Debris flows appear to have left the main channel at various distances from the apex (supplementary movie). In general, maximum runout seems to be larger to the north of this channel (supplementary movie S9) [*Bollschweiler and Stoffel*, 2010]. While there are no pronounced long-term shifts in the locus of deposition, there is evidence for rapid avulsions between successive flows. For example, between flows 4 and 5, and again between flows 15 and 16, a series of short flows near the apex was followed by a sharp shift to the south into an alternate pathway.

These shifts cannot be directly explained by the average present-day fan gradients (Fig. 11b), as these are roughly similar on both sides of the channel. Gradients on the northern flank are slightly higher at the distal part of the fan, which may explain the very gradual northward shift since debris-flow events 17-18.

3.2.5 Aksay

The Aksay fan is the largest debris-flow fan in the Ala-Archa National Park in Kyrgyzstan (Fig. 1h). Past debris flows on the Aksay fan have been triggered either by glacial lake outburst floods or as a result of intense rainfall. The timing and spatial extent of past debris-flow activity has been reconstructed by *Zaginaev et al.* [2016] using dendrogeomorphology by identifying the spatial extent of affected trees per event. In total 26 debris-flow events were reconstructed spanning the period 1877-1999.

At least 15 events have affected large parts of the cone, namely events 2, 5, 7, 9, 12, 13, 14, 15, 16, 17, 18, 19, 20, 23, 24) [*Zaginaev et al.*, 2016]. These were large volume events, and breakouts from the main channels usually occurred right at the fan apex. In contrast, smaller volume events were typically routed by the existing channels and occupied smaller parts of the fan.

The oldest reconstructed events were concentrated on the northern side of the Aksay fan (Fig. 12). During the very large, long-runout flow 14, a southern pathway appears to have opened up. The following debris flow occupied this channel, after which activity switched between the northern and southern pathways until event 25. A major southward avulsion during event 26 established the southern pathway as the main channel on the fan, and recent Google Earth imagery (October 2015) shows that it is still the active channel (Fig. 1h). Note that activity on the southern part of the fan may in reality have been more frequent, as trees are relatively scarce on this part of the fan so that some events that affected this part of the fan may not have been recorded in tree-ring data.

3.2.6 Chalance

The Chalance fan is situated in the Valgaudemar Valley in the French Alps (Fig. 1i). Based on lichenometry 14 debris-flow deposits were dated on the surface of the Chalance fan, ranging between 1806 and 1996 (supplementary image S1) [*Helsen et al.*, 2002]. Associated debris-flow volumes were estimated by *Helsen et al.* [2002] based on deposit dimensions.

The oldest reconstructed debris flows on the Chalance fan were concentrated on the western part of the fan (Fig. 13a). Flow 3 had two distinguishable lobe deposits, one on the distal and one the proximal part of the fan. This proximal deposit likely blocked the entrance of the western debris-flow channel, forcing the next flow to the eastern side of the fan. Flow 5 was a small event that further blocked the western channel near the fan apex, forcing subsequent activity to focus on the eastern part of the fan (Fig. 13). Flows 6-12 show evidence for progressive backstepping within the channel, as shown by progressively smaller runout distances and progressively smaller flow volumes. Flow 10 bifurcated near the fan apex, most likely by the formation of a channel plug during flow 9, opening up a new pathway through the center of the fan (flow angles 5-20°) that was subsequently also occupied by flows 13 and 14 to become the main channel on the fan.

The observed patterns highlight the effect of apex plugging on the avulsion process, as well as the importance of topographic compensation, where activity and deposition on the west is followed by avulsion to the east and subsequent backstepping of the eastern channel. Backfilling of the eastern channel then forced avulsion to the middle part, which is likely to have been the topographically lowest part of the fan as it had no deposition since at least 1806.

3.2.7 Bachelard Valley debris-flow fans

Blijenberg [1998] used dendrogeomorphology and lichenometry to date debris-flow deposits on five small and steep debris-flow fans in the upper Bachelard Valley and the Vallon de la Moutiére, southern French Alps (Fig. 1j-l). The reconstructed debris-flow deposits cover large parts of the surface and therefore capture multiple avulsions. We infer depositional trends from the maps published in *Blijenberg* [1998, their Fig. 9.5], which show elevation on their vertical axis and lateral distance on their horizontal axis (see supplementary movies S10-S13).

Based on these maps it is hard to define an apex location for fans TCP, TGW and TdP. As a result, we analyze the trends based on the relative lateral position of the deposit snouts (rather than the angle from the apex as done in the analyses of the other studied fans) and define runout only relatively (Fig. 14).

The main locus of activity generally shifts gradually from one side of the fan to the other on all fans. This is punctuated, however, by abrupt shifts at the event scale (e.g., flows 3 to 4 on TdP, flows 7-9 on TGE/TGW) (Fig. 14 and supplementary movies). Presumably, the gradual shifts from one side of the fans to the other are driven by topographic compensation, forcing the flows from a relatively high to relatively low area on these fans in small lateral steps.

3.3 Fan sector reconstructions

The chronology of activity on different fan sectors was determined on the Illgraben fan by *Schürch et al.* [2016] (Fig. 1m) and on the Shepherd Creek fan by *Dühnforth et al.* [2007] (Fig. 1n) based on cross-cutting relationships between different lobes, variations in surface morphology and cosmogenic nuclide exposure dating.

3.3.1 Illgraben

The Illgraben fan is located in the Rhône Valley in the Swiss Alps. The oldest debris-flow deposits on the Illgraben fan are located on the western part of the fan (Fig 15a). Here depositional activity shifted radially from the western margin of the fan towards the midwestern part of the fan (sectors 1-3). Subsequently, there was a large avulsion that shifted activity towards the eastern part of the fan (sector 4). Next, activity shifted back to the western margin of the fan (sector 5), after which activity downlapped on sectors 1-3, forming sectors 6-7 around 1600 BP. Then a large shift in the locus of deposition caused debris-flow activity to focus on the eastern part of the fan (sector 8). The locus of deposition backstepped towards the apex to form sector 9 around 1400 BP, after which activity switched back to the northwestern (sector 10) and central (sector 11) parts of the fan around 800 BP.

As suggested by *Schürch et al.* [2016], the pattern of deposition on the Illgraben fan is consistent with repeated lateral and radial shifts in the locus of debris-flow deposition (e.g., sectors 5-6-7 and 10-11) (Fig. 15). Cross-cutting relationships between the lobes show that avulsions have been both local and global in scale, and must have therefore involved avulsion nodes at a range of different radial positions. The presence of downlapping relationships between successive lobes are consistent with backstepping of deposits toward the fan head prior to global avulsion (sector 6 onto 2, 7 onto 3, 9 onto 8, and 10 onto 7).

As measured from the main apex of the Illgraben fan, located directly to the east of the northernmost limit of the rock avalanche deposit (RA in Fig 15a), the western part of the fan is slightly steeper ($\sim 1^{\circ}$) than the eastern part of the fan (Fig 15b). A topographic advantage of the eastern part of the fan may therefore explain the recent east to west shift on the Illgraben fan (sectors 8-9 to 10-11).

3.3.2 Shepherd Creek

The Shepherd Creek fan is located on the western flank of Owens Valley in eastern California, USA. The oldest exposed sector of the Shepherd Creek fan formed more than $\sim$80 ka on the proximal, northern, part of the fan (Fig 16a). After abandonment of this sector, debris-flow activity backstepped toward the fan apex, leading to deposits of sector 2 that downlap onto sector 1 [*Dühnforth et al.*, 2007]. Sector 2 was abandoned around 40 ka, and debris-flow activity shifted southward directly adjacent to sectors 1 and 2. Subsequently, deposition shifted further southward onto sector 4, after which the locus of activity backstepped again at around $\sim$20 ka to form sector 5. This sector was abandoned around $\sim$10 ka BP by incision of the fan head and a lateral shift toward the southern margin of the fan (sector 6).

Shifts of the active parts of the fan sector on the Shepherd Creek fan thus follow sequences of backstepping (e.g., sector 2 onto 1 and sector 5 onto 4), followed by lateral shifts of the locus of activity (e.g., sector 3 following 1-2 and sector 6 following 4-5). Interestingly, the avulsion angles are relatively small, leading to a gradual shift in the locus of deposition from the northern margin of the fan towards the southern margin of the fan.

On the present-day fan, the northern side of the fan, represented by the oldest lobes, forms the steepest and thus topographically most efficient parthway down the fan (Fig 16b). The very deep apex channel incision ($>$30 m deep), however, forces debris-flow activity to the southern side of the fan. This illustrates how apex channel incision may delay topographically-driven avulsions on debris-flow fans.

4 Discussion

4.1 Avulsions on debris-flow fans

Our extensive analysis of observed and reconstructed spatio-temporal patterns of debris flow fan deposition highlight two prominent factors controlling avulsion: (1) an abrupt change in channel position at the time scale of individual surges or flows, likely driven by the occurrence of channel plugs; and (2) a gradual shift in the predominant transport pathway and locus of deposition over the course of multiple flows, allowing fan-scale compensation in response to surface gradients.

Good examples of abrupt switches between successive flows can be found on debris-flow fans in the Swiss Alps, including the Ritigraben, Grosse Grabe, Bruchji, and Birchbach fans (Figs 8-11). At the Kamikamihori, Ohya and Chalk Creek fans, detailed measurements of topographic changes between flows reveal that avulsions are always preceded by the formation of channel plugs deposited as one or more debris-flow lobes (Figs 3-7). Plug formation, in turn, requires flows that block a substantial portion of the channel, and that deposit material in a location from which alternative pathways can be accessed by future flows. This is often, but not always, a location near the fan apex, where different transport pathways converge and a large number of older channels may be found in a restricted area. Especially low mobility flows, either caused by small volume or flow composition, are thus prone to plug a channel and induce avulsion. The stochastic nature of channel plug formation, and its dependence on factors such as debris-flow volume, composition and rheology, may explain the apparently chaotic avulsion behavior and large shifts in the locus of activity observed on the surge to event scale on the studied debris-flow fans.

Although the spatio-temporal patterns of deposition can appear chaotic, avulsions generally follow a pattern of channel plugging, backstepping, avulsion and establishment of a new active channel, perhaps accompanied by incision into older deposits. On the Kamikamihori and Ohya fans (Figs 5,7, supplementary movies S3-S5), the formation of a persistent channel plug is often followed by backstepping of subsequent debris-flow lobes, where the local decrease of gradient induced by lobe deposits forces deposition of subsequent flows upstream of the plug. This leads to a local obstruction and a decrease in channel depth, making it relatively easy for subsequent flows to avulse out of the active channel. After the formation of a channel plug, avulsion occurs during the first debris flow that has a large enough volume to (1) leave the active channel upstream of the plug and (2) carve a new channel or reoccupy an abandoned channel. In contrast, smaller debris flows will simply deposit upstream of the channel plug leading to further backstepping and in-channel deposition. This suggests that avulsions and the spatio-temporal patterns of debris-flow activity on a fan depend strongly on the magnitude-frequency distribution of the debris flows feeding a fan and the associated sequence of event sizes (Fig. 17); we would expect avulsions to be favored on fans with a wide range of flow volumes, but with a sufficiently-large number of small flows to allow plug formation.

Cycles of channel plugging, backstepping, avulsion and channelization are more difficult to recognize on those fans where the locus of activity has been reconstructed by dendrogeomorphology. This may be due to the fact that plugging and backstepping occur in the active channel of a debris-flow fan where trees are generally absent. Only the relatively large events that are able to leave the main channel are preserved in the tree-ring record, which probably also explains why the events that are reconstructed by dendrogeomorphology often cover large parts of the fan surface (e.g., Figs 8, 9, 12). Nevertheless, reconstruction of the Ritigraben fan and geomorphic observations of the present-day surface of this and other fans show the presence of many debris-flow plugs in abandoned channels [e.g., *Bollschweiler et al.*, 2007, 2008; *Stoffel et al.*, 2008], which suggests that avulsions on these fans may also be preconditioned by the formation of channel plugs.

On larger spatial and temporal scales (e.g., the Illgraben and Shepherd Creek fans; Figs 15, 16), avulsion between entire fan sectors follows similar patterns of backstepping and lateral shifts as we observe at the event scale. Despite the marked scale difference of such sectors compared to individual lobes, backstepping appears to be governed by similar topographic forcing mechanisms. Activity on a fan sector eventually decreases the fan gradient, at least locally, forcing subsequent debris-flow activity to deposit upstream of this sector and causing backstepping toward the apex. Once backstepping has significantly decreased channel depth and fan slopes, the locus of activity may shift towards a topographically lower part of the fan.

This brings us to the second avulsion mechanism: on many of our fans, the average locus of deposition is observed to move towards the topographically lowest areas, often over the course of multiple debris flows. Debris-flow activity often alternates between the old and new pathway for a number of events before the former channel is finally abandoned (e.g., the Ohya, Ritigraben, Bruchji, and Chalk Creek fans), although shifts are abrupt on other fans (e.g., the Kamikamihori and Chalance fans). The approximate direction of the shift is generally predictable on the basis of surface gradients measured from the apex on the present-day topography (e.g., Figs. 5, 8).

Repeat topographic observations on the Chalk Creek, Ohya and Kamikamihori fans reveal that debris flows often follow the steepest pathway down the fan, and that flow is often routed down suitably-oriented abandoned channels. These observations indicate the importance of topographic compensation in driving longer-term evolution of debris-flow fans. *Pederson et al.* [2015] showed evidence for fan-scale compensational behavior on three debris-flow fans in Colorado. Note that compensational behavior in our fans typically occurs only across sequences of flows, rather than between successive flows. This observation defines a characteristic persistence time scale for each fan, expressed in terms of the number of flows; over shorter periods than this time scale, the orientation of the transport pathway is essentially persistent, while over longer time periods the system approaches full compensation. Comparable transitions between short-term persistent and long-term compensational behavior have been noted on a range of natural and experimental fluvial and turbidite fans [*Straub et al.*, 2009; *Wang et al.*, 2011; *Straub and Pyles*, 2012; *Van Dijk et al.*, 2016].

4.2 Effects of large flows on avulsion behavior

Large flows play an important but variable role in triggering avulsion on debris-flow fans. On the Kamikamihori fan, avulsion often takes place during relatively large events that are able to leave the main channel and have sufficient volume or momentum to excavate or build a new channel or flow a substantial distance down an older channel. Whether flow volume, depth, momentum, or composition is the critical parameter to ensure avulsion success partly depends upon the controls on flow entrainment and bed erosion, which remain poorly understood [e.g., *Schürch et al.*, 2011; *Iverson et al.*, 2011; *Iverson*, 2012; *De Haas and Van Woerkom*, 2016]. Regardless, our observations show that avulsion in a large flow can only occur after the channel has been plugged, which is often the result of deposition by one or more smaller flows. This suggests that there may be a favorable sequence of debris-flow events to trigger avulsion: small to moderate events lead to channel plugging and infilling, producing a relatively shallow spot in the channel that is prone to avulsion. A large debris flow that follows may then leave the main channel here and create a new pathway for future flows. Conversely, a sequence of large flows is more likely to remain in and perhaps enlarge the main channel, as debris-flow erosion appears to scale with flow depth [e.g., *Berger et al.*, 2011; *Schürch et al.*, 2011; *De Haas and Van Woerkom*, 2016].

Large flows can also lead to deposit plugs and avulsion, especially where debris is split between multiple channels or where a coarse-grained flow forms a large, but relatively immobile, flow front that reduces runout [e.g., *Major and Iverson*, 1999; *De Haas et al.*, 2015b]. This happened for example during the extremely large 1922 event on the Ritigraben fan (event 19 in Fig. 8, supplementary movie S6), which formed a very large lobe deposit on the proximal part of the fan. This lobe triggered a major avulsion and controlled the patterns of debris-flow activity on the fan in at least 15 subsequent flows (and continuing up to the present day) by blocking the proximal entrance to the central pathway on the fan.

Large flows may also be important if they form multiple surges. As debris-flow volume increases the flow front generally does not grow in size proportionally, but instead there is often an increase in the number of surges, each of which can form a separate depositional lobe [e.g., *Suwa and Okuda*, 1983]. As such, large debris flows may behave as a series of smaller-scale flows wherein the different surges behave as otherwise individual events. For example, during the large debris-flow events that affected the Kamikamihori fan on 22 August 1979 (Fig. 7, Supplementary movie S5), multiple sequences of channel plugging, backstepping, avulsion and new channel formation were observed, similar to the sequences that are normally formed over multiple debris-flow events.

4.3 Avulsion frequency on debris-flow fans

The repeat topographic observations on the Chalk Creek, Ohya and Kamikamihori fans, along with the detailed reconstruction of flows on the Chalance fan, allow us to place rough constraints on avulsion frequency. This analysis cannot be extended to the fans on which debris-flow events are reconstructed from tree-ring data, because the number of debris flows that remain in the main channel is unknown for these fans. For the purposes of calculating avulsion frequency, we define avulsions as those events that occupy a channel other than the main channel. Secondly, we talk about a major avulsion once the main debris-flow activity has fully switched from one channel to another.

On the Kamikamihori fan, 4 out of 19 events resulted in major channel shifts (August 1979, September 1979, September 1983 and July 1997 in Figure 7). A major avulsion thus occurred on average once in every $\sim$5 flows. This average is consistent with the most recent activity in the southern and northern channels, which have been occupied from 1983 onwards. In the southern channel, 7 debris flows occurred between 1983 and 1996 before an avulsion occurred, while 6 debris flows have occurred in the northern channel since its formation in 1997, suggesting a major avulsion frequency of once in every 6-7 flows since 1983.

On the Ohya fan, 23 debris-flow events occurred between 2005 and 2013 (Fig. 5). Flows left the main channel to occupy channels in the center and east of the fan at least once in the periods 2006-2009, 2010-2011 and 2012-2013. As such, there have been at least 3 avulsions in 23 events on the Ohya fan, corresponding to an avulsion every ∼8 flows. The channel on the western margin of the fan, however, has remained the main channel for most of the study period, and only during one of the final events in 2012-2013 might the central channel have routed the main debris-flow discharge. This results in a minimum major avulsion frequency of once in every 23 flows.

On the Chalk Creek fan, it took at least 8 debris flows between May 2009 and July 2011 to completely shift the dominant locus of deposition from the southern to the northern side of the fan (Fig. 3). This suggests a maximum major avulsion frequency of once in every 8 flows.

On the Chalance fan large shifts in the locus of deposition occurred during debris flows 4, 5, 6 and 14. (Fig. 13, supplementary image S1). Averaged over the 14 reconstructed flows, this leads to a major avulsion every ∼4 flows. The avulsion frequency is, however, highly variable, with avulsions occurring in each flow during events 4-6 while a sequence of 7 events occurred before a major avulsion happened during flow 14.

In short, avulsions on the four fans for which we have sufficient data appear to occur approximately every 3-8 flows, but major shifts in the main channel position may require many more events, as shown on the Ohya fan. We note that these numbers are based on a few fans only and are inferred from a small number of debris flows. As such, the inferred avulsion frequencies are tentative at best and should not be generalized and transferred to other fan systems without careful consideration. There is a clear need to determine avulsion frequencies on fan systems in other settings in order to identify the first-order controls on both frequency and mechanism. For example, in settings where debris-flow frequency is low and/or rates of secondary modification are high, the topography of inactive fan surfaces is often strongly modified and subdued [e.g., *Frankel and Dolan*, 2007; *Owen et al.*, 2014; *De Haas et al.*, 2014, 2015a; *Cesta and Ward*, 2016; *Dühnforth et al.*, 2017], which may affect avulsion mechanisms and flow path selection after avulsion.

4.4 Comparison with fluvial and experimental fans

Cycles of backstepping, avulsion and new channel formation observed on the natural fans studied here are qualitatively similar to those observed on the experimental debris-flow fan of

De Haas et al. [2016]. However, their experimental fan was built by debris flows with constant volume, composition, and rheology, which rendered avulsion cycles on the experimental debris-flow fans somewhat predictable. In their experiments, backstepping commenced once the accommodation was filled, reducing the local gradient at the end of the main channel. This resulted in progressive backstepping of debris-flow deposits to the fan apex followed by selection of a new flow pathway. This experimentally observed avulsion cycle is very similar to the repeated sequences of avulsion, fan-head incision and backfilling observed on some experimental fluvial fan systems [e.g., *Schumm et al.*, 1987; *Bryant et al.*, 1995; *Whipple et al.*, 1998; *Van Dijk et al.*, 2009, 2012; *Clarke et al.*, 2010; *Reitz and Jerolmack*, 2012]. Channel aggradation on experimental fluvial fans can also be initiated at the fan toe after accommodation is filled, leading to upstream-migrating in-channel sedimentation.

On the natural debris-flow fans studied here, the variations in magnitude, composition and rheology of the flows feeding the fans result in a more chaotic and less predictable avulsion pattern than has been found in the experimental debris-flow and fluvial fans. A second key difference with fluvial fan systems is that, rather than aggradation occurring progressively over the entire channel length, the thick lobe deposits of debris flows provide a mechanism for rapid local aggradation of up to a full channel depth (or more) at any location in the main channel, behind which backstepping and avulsion can occur [e.g., *Beaty*, 1963; *Suwa and Okuda*, 1983; *Whipple and Dunne*, 1992]. Thus, unlike in the experiments and on fluvial fans, backfilling need not occur along the whole pathway in order to trigger an avulsion. As a result, on debris-flow fans avulsions may be more easily triggered in a single event, potentially leading to higher avulsion frequencies, less predictable avulsion locations, more chaotic spatio-temporal patterns of fan formation and perhaps different compensational behavior compared to fluvial fans.

A consequence of channel plugging on debris-flow fans is that large sections of debris-flow channels can become abandoned without undergoing aggradation or resurfacing. These remnant channels, preserved on the fan surface, can play an important role in flow routing following later avulsions. Our results show that it is common for debris flows to follow abandoned channels after avulsion (e.g., Chalk Creek, Ohya and Kamikamihori fans; Figs. 3, 5, 7, supplementary movies S1-S5), and further analyses of this effect may be important for future flow path prediction. The tendency of rivers to reoccupy former paths has been observed repeatedly in the field and in stratigraphic records [e.g., *Mohrig et al.*, 2000; *Aslan et al.*, 2005; *Jerolmack and Paola*, 2007]. *Aslan et al.* [2005] proposed that channel reoccupation occurs because previous channels provide ready paths across the floodplain in fluvial systems, and the same appears to hold true for debris-flow fans where abandoned channels also provide ready and efficient paths down a fan. *Reitz et al.* [2010] found that reoccupation dynamics on fluvial fans were similar to a system in which path selection occurs as a random walk to the shoreline, but channels reoccupy previous paths if they intersect. On the Ohya fan we see the same thing happening during the period 2012-2013, in which the newly formed channel follows a new flow path towards the center of the fan until it encounters the channel that was active in 2006-2008 and 2010-2011, after which it occupies and follows this channel downfan (Fig. 5).

4.5 Implications for debris-flow hazards

While prediction of specific avulsions on debris-flow fans is challenging, mainly as a result of the stochastic nature of channel plug formation, our results show that the occurrence of channel plugs or lobe deposits in the active channel, perhaps combined with backstepping sequences in recent flows, may be good indications of the sites of potential or impending avulsion. Channel depth typically decreases downstream from the apex [e.g., *Okuda et al.*, 1981], implying that thicker channel plugs are needed for avulsion to occur near the fan apex compared to further downstream. However, debris-flow lobe thickness generally also decreases from fan apex to toe [*Suwa and Okuda*, 1983; *Whipple and Dunne*, 1992; *Stoffel et al.*, 2008; *Schneuwly-Bollschweiler et al.*, 2013]. Understanding the balance between the longitudinal channel depth and lobe deposit thickness variation may thus be a useful way of identifying avulsion 'hotspots', where channel depths are comparable to typical flow or lobe thicknesses.

Furthermore, the compensational tendency of our fans over longer time scales indicates that avulsion-prone fan sectors may be identified in advance by analyzing the radial variations in fan topographic slope. Abandoned channels, particularly those on such avulsion-prone fan sectors, can be expected to become preferred pathways on a debris-flow fan following a future avulsion. These observations can be used to provide some guidelines on when and where to apply preparation or mitigation measures. While there is a propensity for debris flows to follow existing pathways, this is not to suggest that they will be constrained to these pathways. The large debris flows reconstructed in the dendrogeomorphology portion of our analysis indicate that significant areas can be inundated. Furthermore, more work needs to be conducted on understanding how the debris-flow dynamics are modified by the pre-existing channel and how this could increase or decrease risks in areas adjacent to or downstream of the channel [*Wasklewicz and Scheinert*, 2016].

Our results further enable the identification of some important directions for future research in order to better understand and predict debris-flow avulsion, and thereby enhance the efficiency of mitigation measures. Our results show that the magnitude-frequency distribution and the associated volume sequence of flows entering a fan is likely to strongly affect avulsion frequency (Fig. 17). Channel plugs are more likely to be formed by small- to moderately-sized flows, whereas only relatively large flows are more prone to leave the main channel and form a new pathway down the fan, especially in the presence of a channel plug. As such, systems in which large flows are relatively abundant - that is, fans with a flow magnitude-frequency distribution that is particularly heavy-tailed - may thus be less prone to avulsion because of the paucity of smaller, plug-forming flows and the tendency of large flows to entrain material as they transit the fan [*Schürch et al.*, 2011]. On the other hand, a proportional deficiency of large flows may also result in a lower avulsion frequency, because there are fewer flows with sufficient volume to leave the main channel and form a new channel. This suggests that, in a given catchment and with a given set of flow characteristics such as composition and bulk rheology, there may be an optimal debris-flow magnitude-frequency distribution which maximizes the likelihood of avulsion.

To better understand debris-flow hazards on fans, it is thus important to further explore the feedbacks between the magnitude-frequency distribution of the debris flows feeding a fan and avulsion patterns and tendencies. This is especially relevant if magnitude-frequency distributions are expected to change as a result of global climate change [e.g., *Stoffel*, 2010; *Clague et al.*, 2012] or regional factors such as earthquakes [e.g., *Shieh et al.*, 2009; *Huang and Fan*, 2013; *Ma et al.*, 2017] or wildfires [e.g., *Cannon et al.*, 2008, 2011]. Moreover, successions of debris flows causing avulsion may occur over very short timescales as indicated by *Suwa* [2003] and *Suwa* [2017]. They show that successions of multiple debris flows leading to avulsion can occur within less than a day, which has important implications for hazard mitigation.

5 Conclusions

This paper documents generic spatio-temporal patterns of debris-flow fan evolution and determines two common processes controlling avulsion on debris-flow fans. This is done by compiling and analyzing a dataset of 16 debris-flow fans for which the depositional history has been directly measured or reconstructed. Where possible the observed spatial and temporal patterns of debris-flow activity are compared to fan topography (e.g., channel plugs, topographic depressions and abandoned channels), to evaluate the effects of topography on debris-flow avulsion and flow routing.

We observe two main mechanisms that control avulsion and that operate on distinct time scales. On the surge to event scale, depositional plugs locally block channels and force subsequent flows to avulse. The frequent but stochastic nature of channel-plug formation can lead to abrupt channel shifts. Over time scales of multiple events (typically 5-20 for the fans studied here), the average locus of debris-flow deposition gradually shifts towards the topographically lower parts of a fan, highlighting the importance of topographic compensation for long-term avulsion behavior and flow-path selection.

Channel plugs can form in flows of all volumes, and their occurrence likely depends at least in part upon flow composition and bulk rheology as well as flow volume. However, plugs are commonly, although not exclusively, observed to form in small to moderate flows, especially those that deposit material. After plug formation, subsequent small to moderate size flows deposit material behind the plug, filling the channel and leading to progressive backstepping of the locus of debris-flow deposition. This process continues until a debris flow occurs of sufficient volume to leave the main channel and establish a new channel. This avulsion sequence suggests that the magnitude-frequency distribution of debris flows feeding a fan as well as the order in which small, moderate and large flows alternate may exert a strong control on the spatio-temporal evolution of debris-flow fans. Avulsions show a strong tendency to re-occupy older channels on the fan surface, leading to persistent deposition on certain sectors of the fan.

On debris-flow fans the avulsion time scale can be small, as local blocking of a channel can be easily attained within a single surge or event by plug formation. This may lead to relatively high avulsion frequencies, more chaotic spatio-temporal patterns of fan evolution, and potentially fundamentally different compensational behavior compared to fluvial fans. While prediction of specific avulsions is challenging, our results show that the locations of channel plugs and backstepping sedimentation may be used to identify sites of potential or impending avulsion. Furthermore, the compensational tendency of our fans over longer time scales indicates that avulsion-prone fan sectors may be identified in advance, potentially allowing preparation or mitigation measures to take place.

Acknowledgments

This work is funded by the Netherlands Organization for Scientific Research (NWO) via Rubicon grant 019.153LW.002 to TdH. Constructive comments by Francesco Brardinoni are gratefully acknowledged. We thank Miriam Dühnforth, Kimberly Hill, Brian McArdell, and Peter Schürch for stimulating discussions on avulsion and debris-flow fan evolution.

Figure 1: Studied debris-flow fans. Dashed white line indicates the fan outline. (a) Secondary fan at Chalk Creek (USA); (b) Fan on the Ohya Landslide (Japan); (c) Kamikamihori fan (Japan); (d) Ritigraben fan (Switzerland); (e) Grosse Grabe fan (Switzerland); (f) Birchbach fan (Switzerland); (g) Bruchji fan (Switzerland); (h) Aksay fan (Kyrgyzstan); (i) Chalance fan (France); (j) TCP and TCP-N1 fans (France); (k) TdP fan (France); (m) TGE-TGW fans (France); (n) Illgraben fan (Switzerland); (o) Shepherd Creek fan (USA). See Table 1 for further fan characteristics. Image source Google Earth, a kmz file with the fan locations is included as supplementary material.

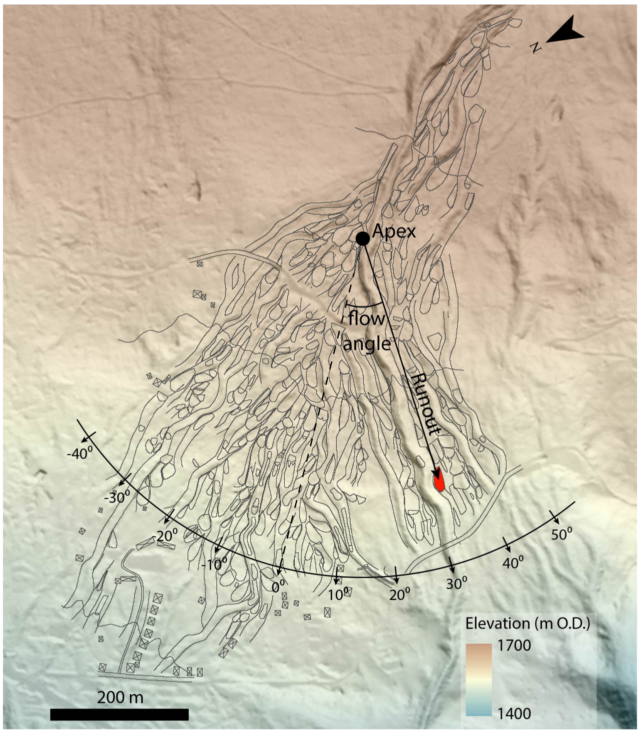

Figure 2: Method for pattern extraction and fan gradient calculation. Red polygon shows a debris-flow lobe deposit. Depositional patterns over time are quantified by the runout distance and flow angle from the fan apex. Average fan slopes are calculated per radial angle at multiples of 100 m from the fan apex. Grey outline marks the mapped debris-flow channels and deposits from [*Stoffel et al.*, 2008].

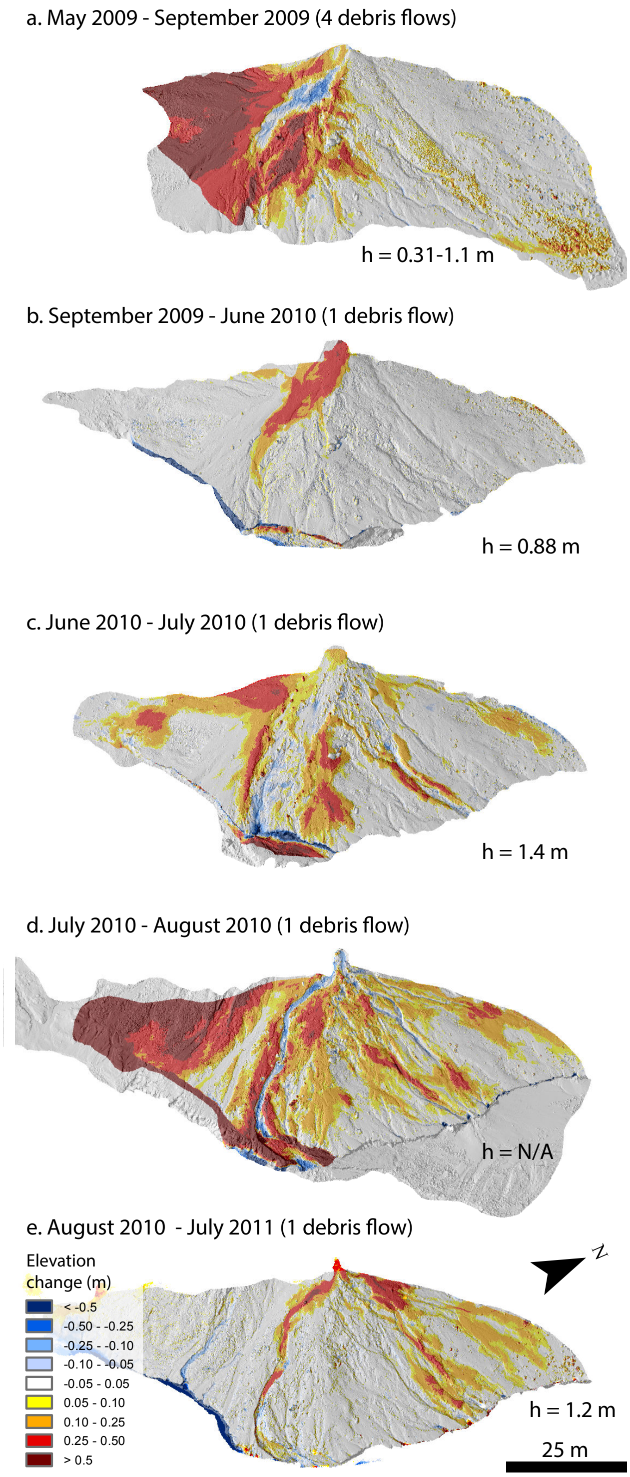

Figure 3: DEMs-of-difference on top of hillshades for the Chalk Creek secondary debris-flow fan [extended from *Wasklewicz and Scheinert*, 2016]. (a) Difference between May 2009 and September 2009, (b) difference between September 2009 and June 2010, (c) difference between June 2010 and July 2010, (d) difference between July 2010 and August 2010, (e) difference between August 2010 and July 2011. To give an idea of the size of the debris flows affecting the fan, the measured flow depth in the catchment area [upstream station in *McCoy et al.*, 2010] is denoted by h in the figure.

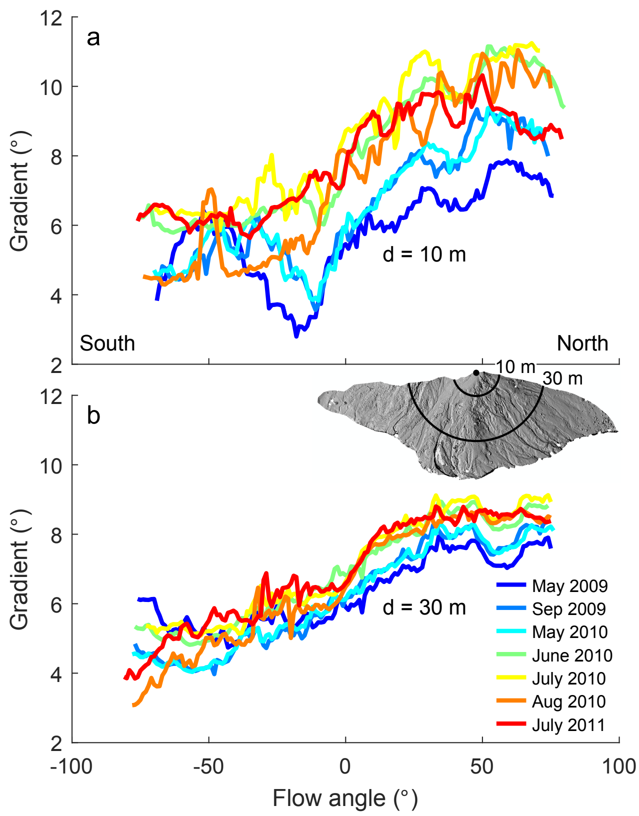

Figure 4: Downfan gradients on the Chalk Creek secondary fan between May 2009 and July 2011. (a) Average gradient from the fan apex to 10 m downfan, (b) average gradient from the apex to 30 m downfan.

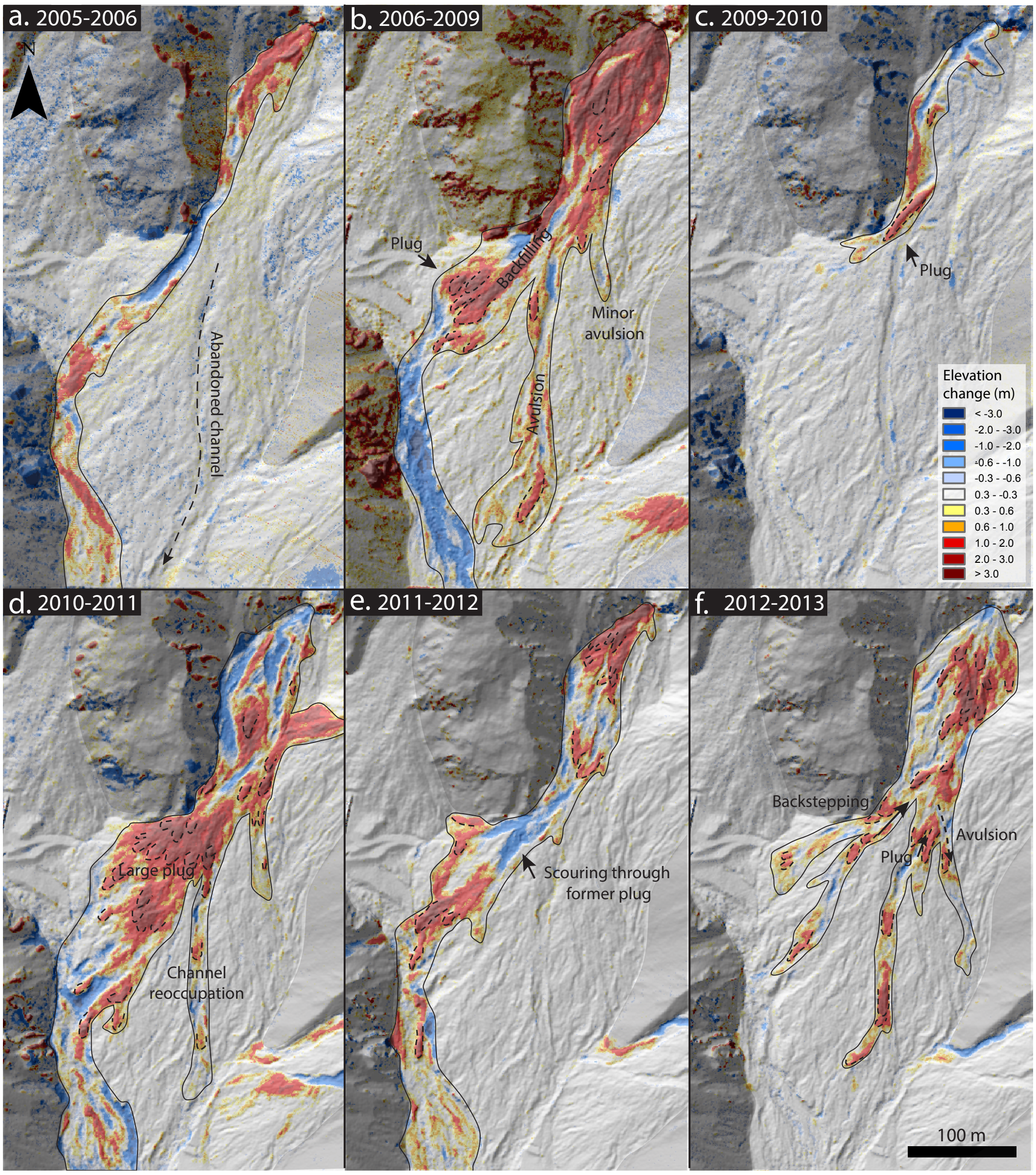

Figure 5: DEMs-of-difference on top of hillshades for the Ohya debris-flow fan [after *Imaizumi et al.*, 2016]. (a) Difference between 2005 and 2006 (4 debris-flow events), (b) difference between 2006 and 2009 (4 debris-flow events), (c) difference between 2009 and 2010 (3 debris-flow events), (d) difference between 2010 and 2011 (5 debris-flow events), (e) difference between 2011 and 2012 (5 debris-flow events), (f) difference between 2012 and 2013 (2 debris-flow events). Solid lines indicate the areas affected by debris flows. Dashed lines indicate distinct debris-flow lobe deposits.

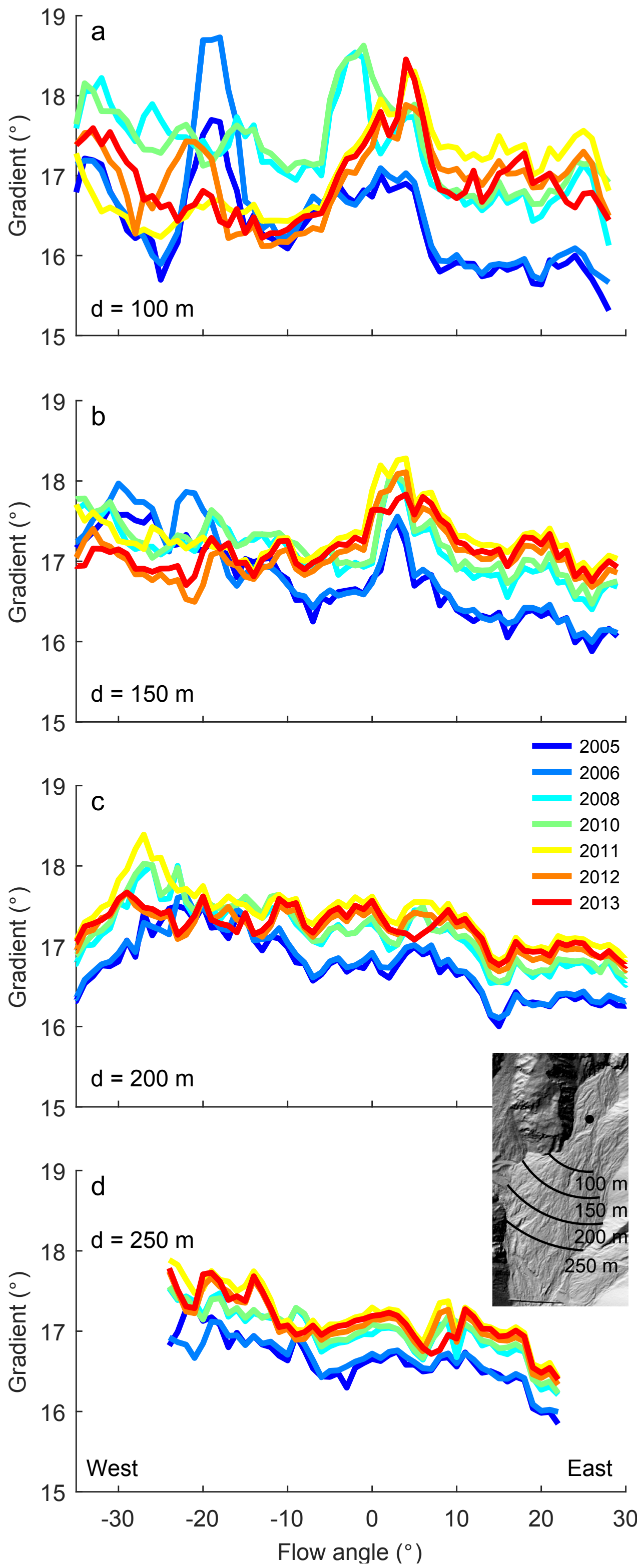

Figure 6: Downfan gradients on the Ohya debris-flow fan between 2005 and 2013. (a) Average gradient from the apex of the main avulsions that occurred between 2005 and 2013 to 100 m downfan, (b) average gradient from the apex of the main avulsions that occurred between 2005 and 2013 to 150 m downfan, (c) average gradient from the apex of the main avulsions that occurred between 2005 and 2013 to 200 m downfan, (d) average gradient from the apex of the main avulsions that occurred between 2005 and 2013 to 250 m downfan.

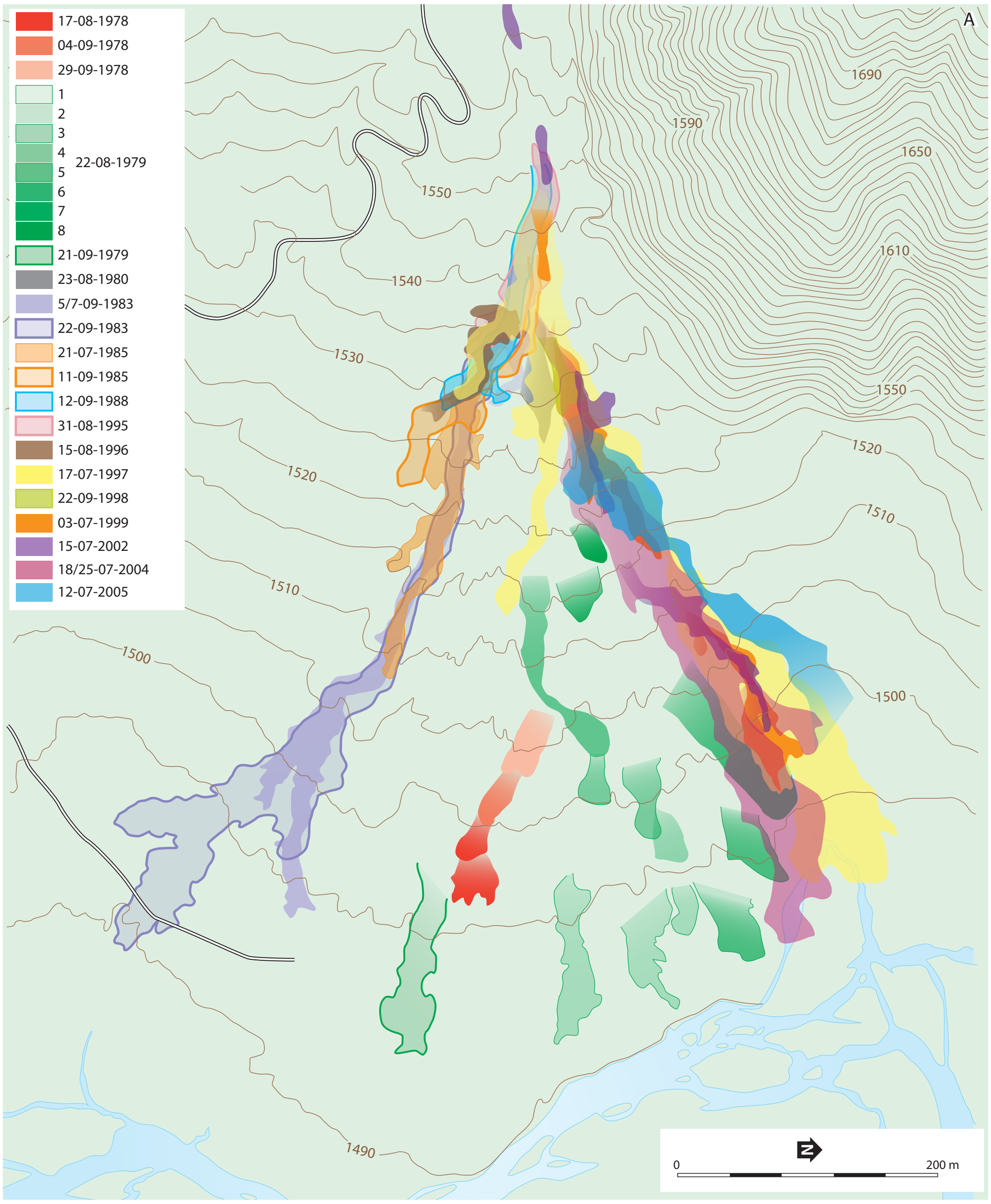
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Figure 7

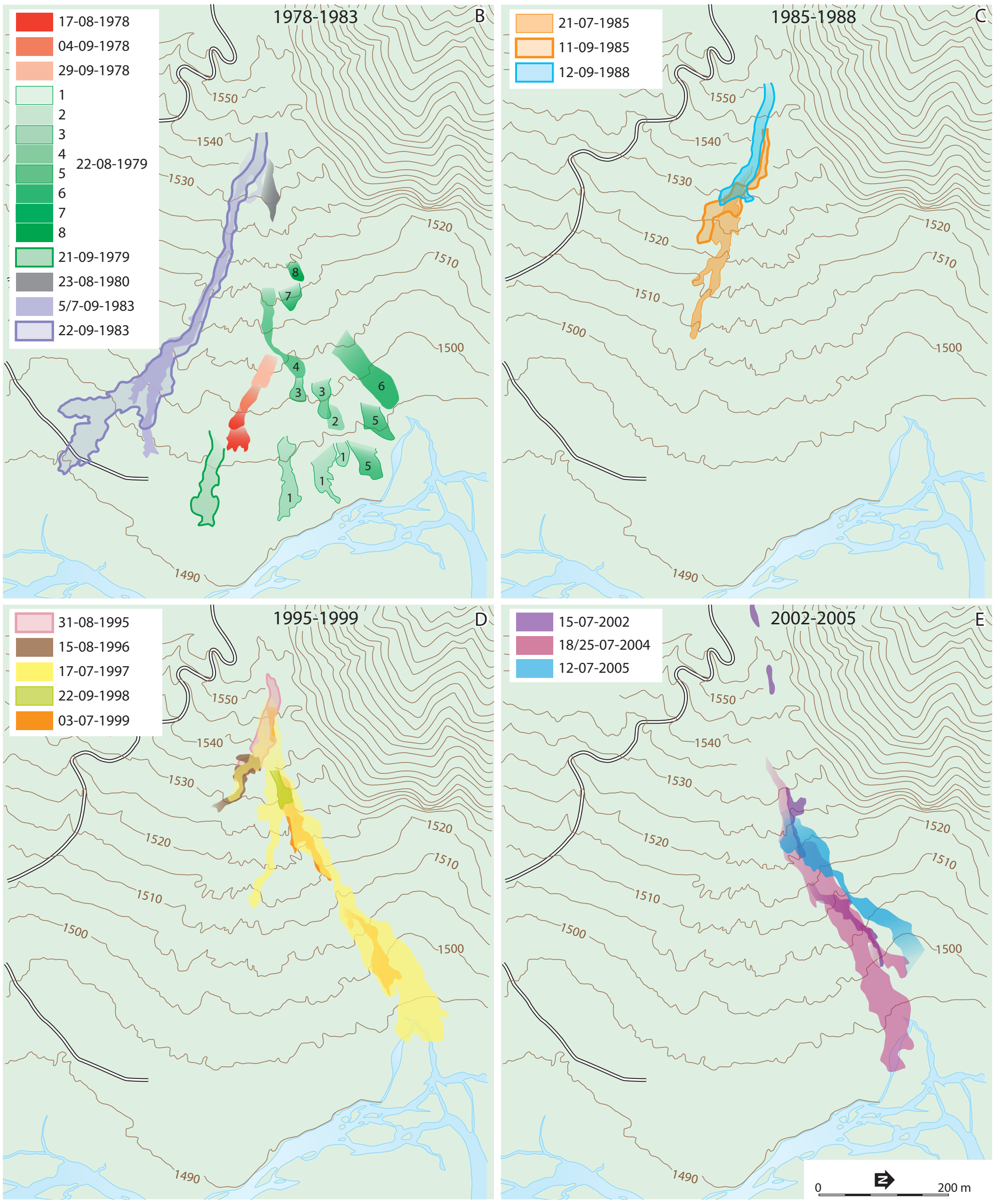

Figure 7: Depositional history on the Kamikamihori fan between 1978 and 2005 (a) Depositional history of all flows. (b-e) Detailed depositional history, highlighting the spatial patterns of activity on the Kamikamihori fan. Data from 1978 to 1997 after *Suwa and Okuda* [1983], *Suwa and Yamakoshi* [1999] and [*Suwa et al.*, 2009]. Data after 1997 is newly presented here.

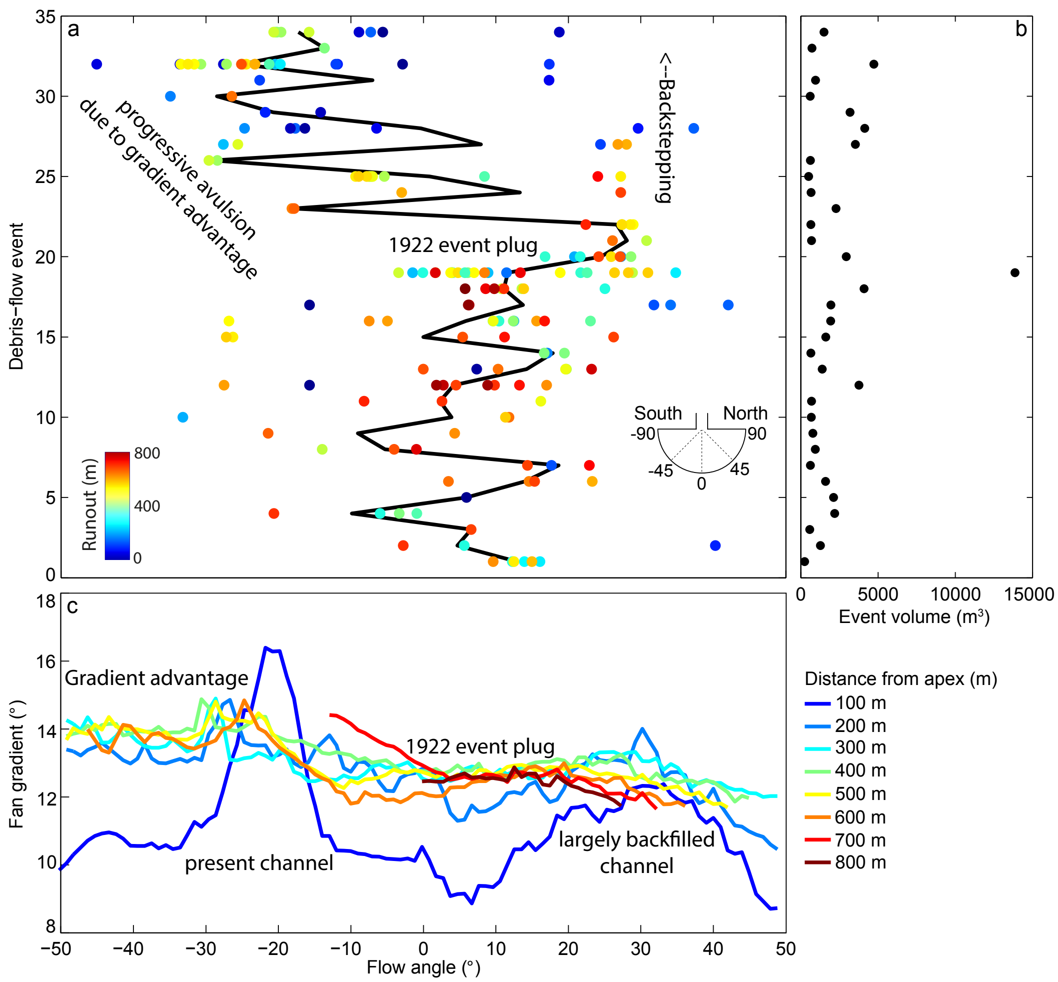

Figure 8: Spatio-temporal patterns of debris-flow activity on the Ritigraben debris-flow fan. (a) Spatial distribution (runout and flow angle relative to the fan apex) of debris-flow lobes per event year based on the dendrogeomorphological reconstructions in *Stoffel et al.* [2008]. The solid line denotes the weighted average flow angle per event year (weight increases linearly with distance from the apex). (b) Estimated event volumes [from *Stoffel*, 2010]. (c) Average fan gradient for radial distances of 100-800 m from the fan apex.

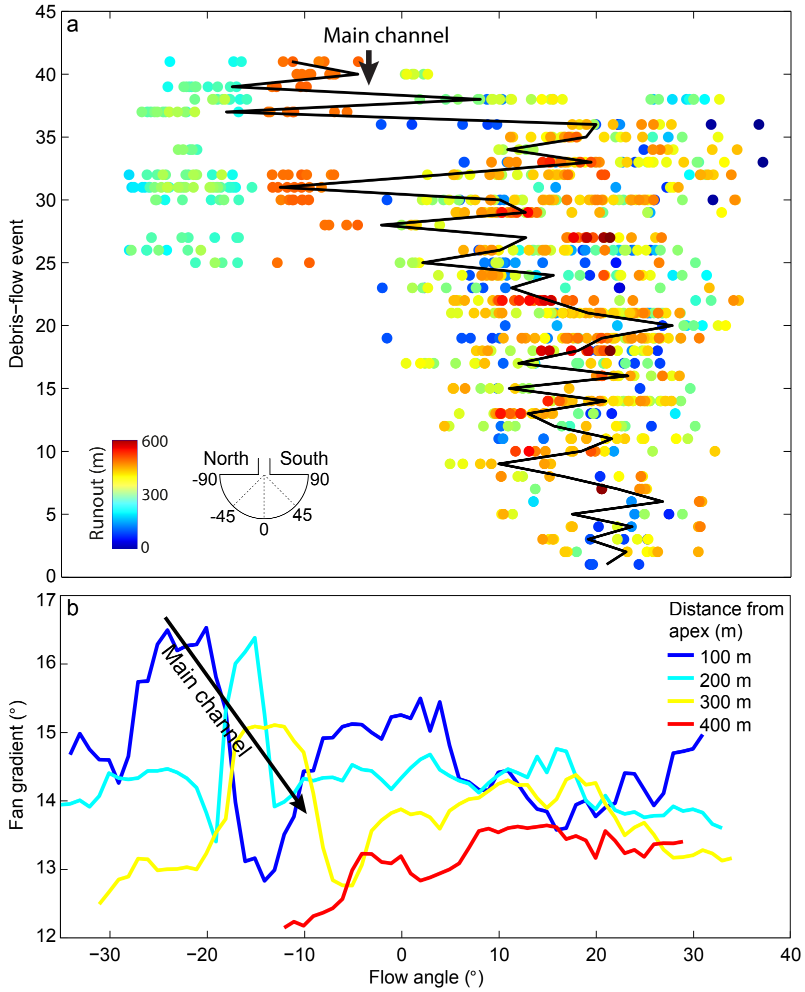

Figure 9: Spatio-temporal patterns of debris-flow activity on the Bruchji debris-flow fan. (a) Spatial distribution (runout and flow angle relative to the fan apex) of affected trees per event year based on the dendrogeomorphological reconstructions in *Bollschweiler et al.* [2007]. The solid line denotes the weighted average flow angle per event year (weight increases linearly with distance from the apex). (b) Average fan gradient for radial distances of 100-400 m from the fan apex.

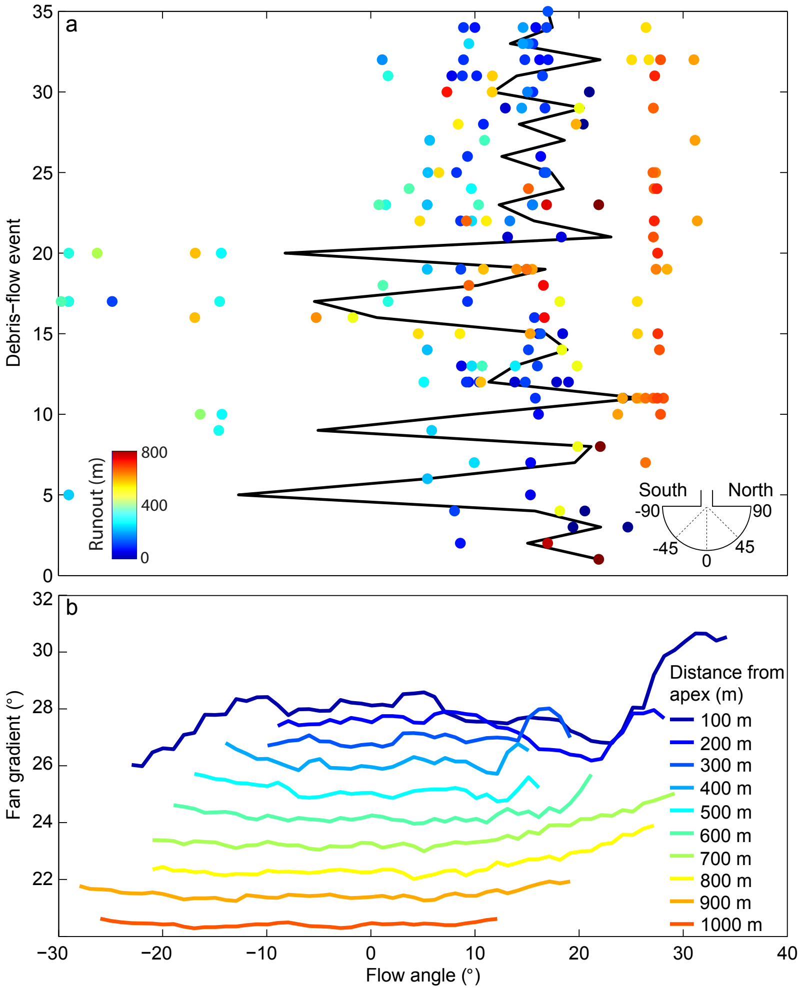

Figure 10: Spatio-temporal patterns of debris-flow activity on the Grosse Grabe debris-flow fan. (a) Spatial distribution (runout and flow angle relative to the fan apex) of affected trees per event year based on the dendrogeomorphological reconstructions in *Bollschweiler et al.* [2008]. The solid line denotes the weighted average flow angle per event year (weight increases linearly with distance from the apex). (b) Average fan gradient for radial distances of 100-1000 m from the fan apex.

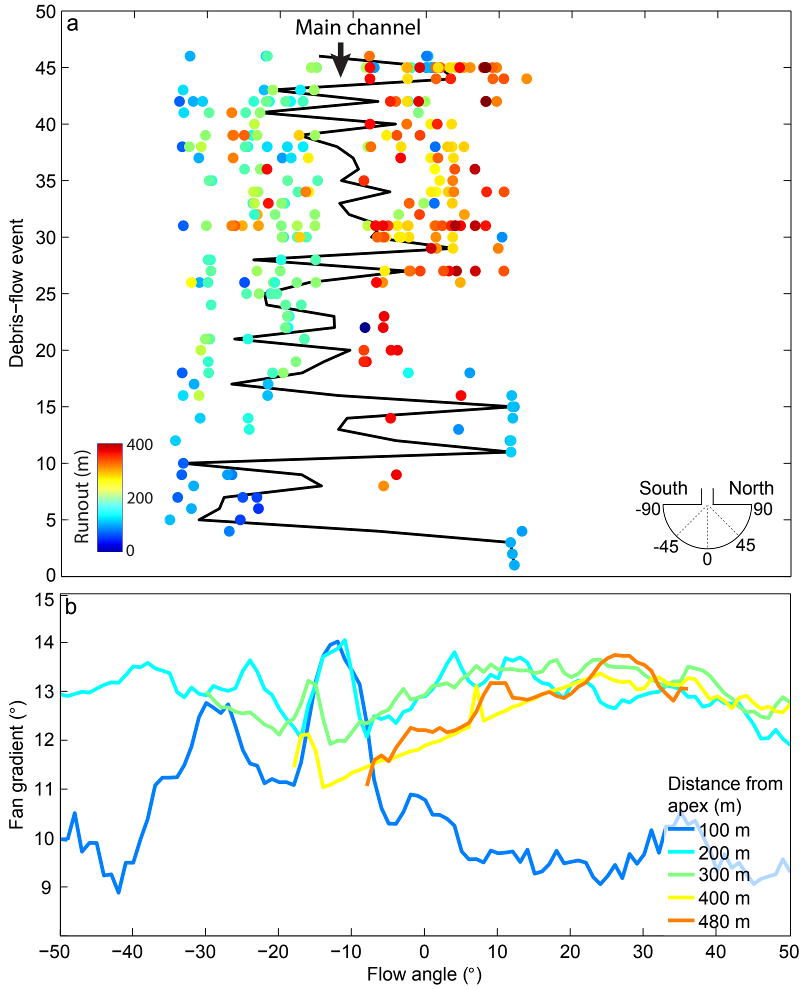

Figure 11: Spatio-temporal patterns of debris-flow activity on the Birchbach debris-flow fan. (a) Spatial distribution (runout and flow angle relative to the fan apex) of affected trees per event year based on the dendrogeomorphological reconstructions in *Bollschweiler and Stoffel* [2010]. The solid line denotes the weighted average flow angle per event year (weight increases linearly with distance from the apex). (b) Average fan gradient for radial distances of 100-480 m from the fan apex.

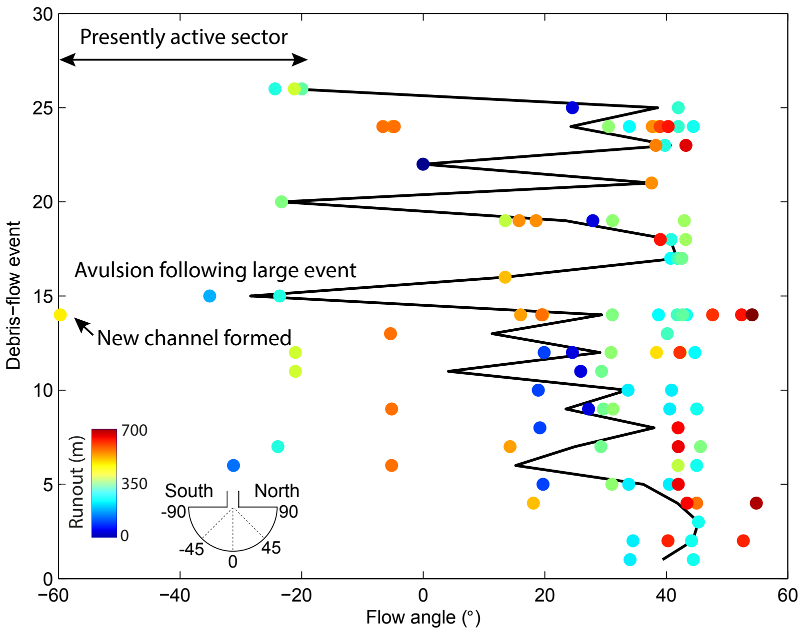

Figure 12: Spatio-temporal patterns of debris-flow activity on the Aksay debris-flow fan, extracted from the spatial distribution (runout and flow angle relative to the fan apex) of affected trees per event year based on the dendrogeomorphological reconstructions in *Zaginaev et al.* [2016]. The solid line denotes the weighted average flow angle per event year (weight increases linearly with distance from the apex).

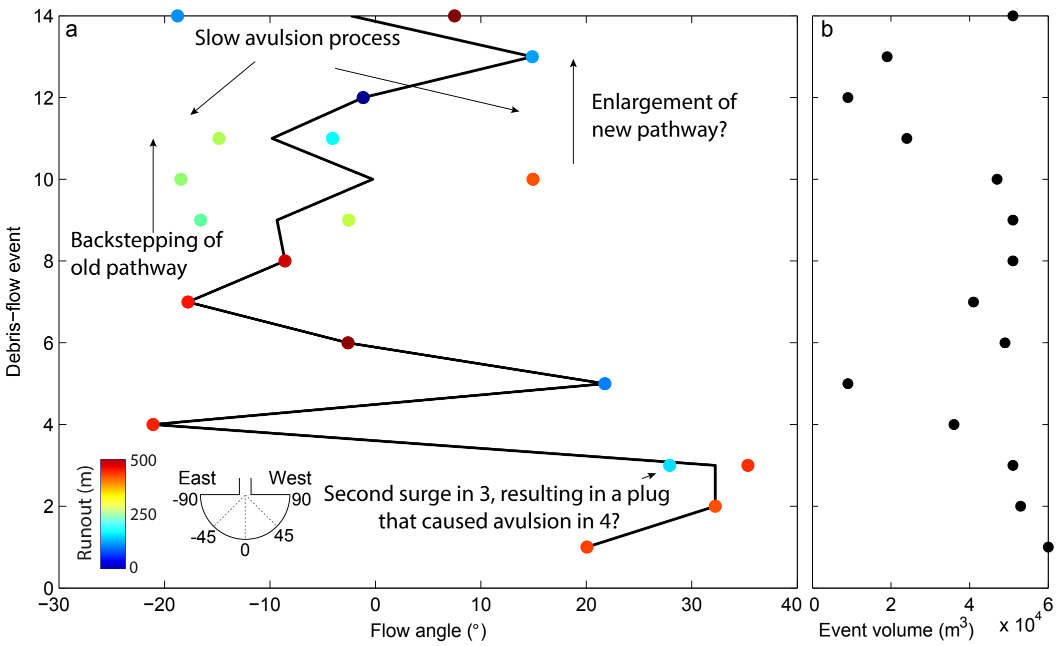

Figure 13: Spatio-temporal patterns of debris-flow activity on the Chalance debris-flow fan. (a) Spatial distribution (runout and flow angle relative to the fan apex) of debris-flow lobes per event year based on lichenometric reconstructions of *Helsen et al.* [2002]. The solid line denotes the weighted average flow angle per event year (weight increases linearly with distance from the apex). (b) Estimated event volumes [from *Helsen et al.*, 2002].

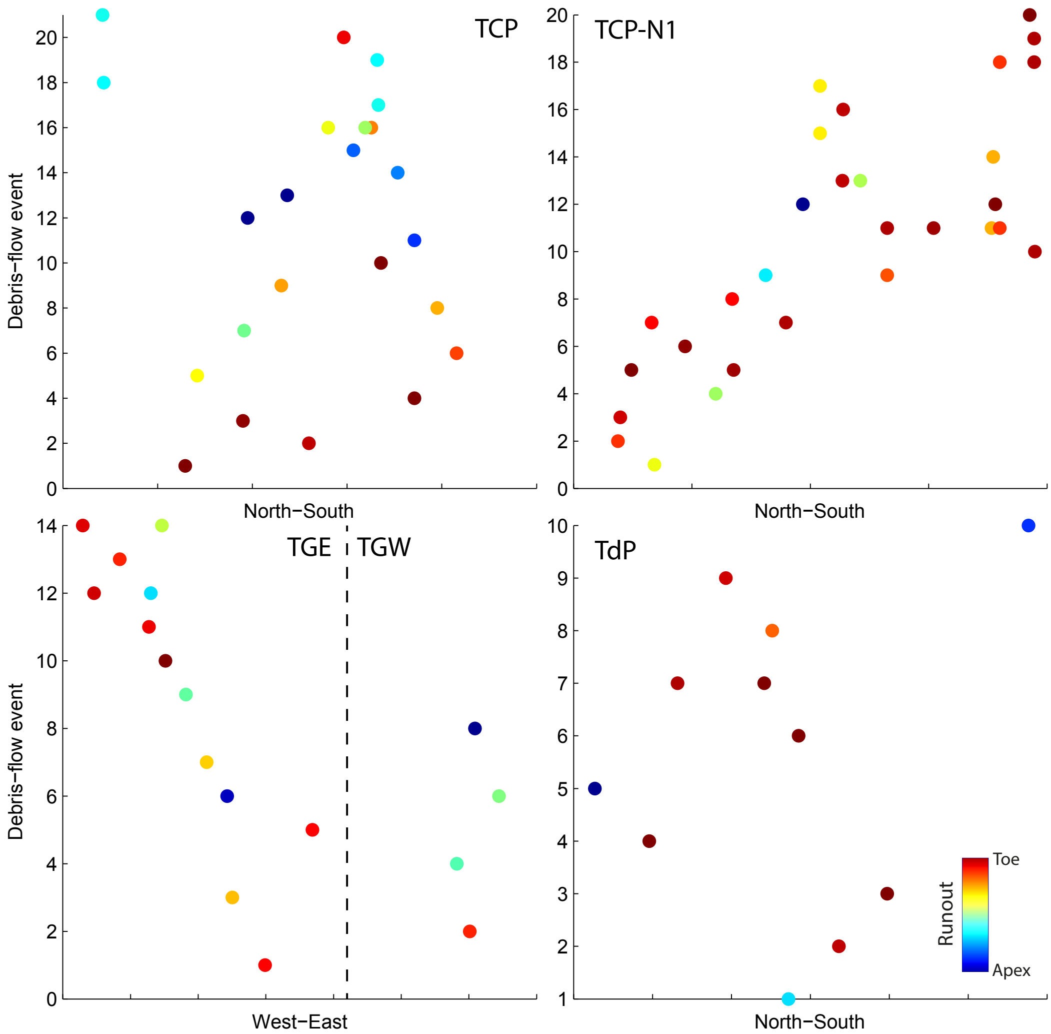

Figure 14: Spatio-temporal patterns of debris-flow activity on five debris-flow fans in the French Alps, extracted from the spatial distribution (runout and flow angle relative to the fan apex) of debris-flow lobes and levees dated with dendrogeomorphology and lichenometry by *Blijenberg* [1998]. Position and runout are relative to other events on the same fan. (a) TCP, (b TCP-N1, (c) TGE and TGW, (d) TdP.

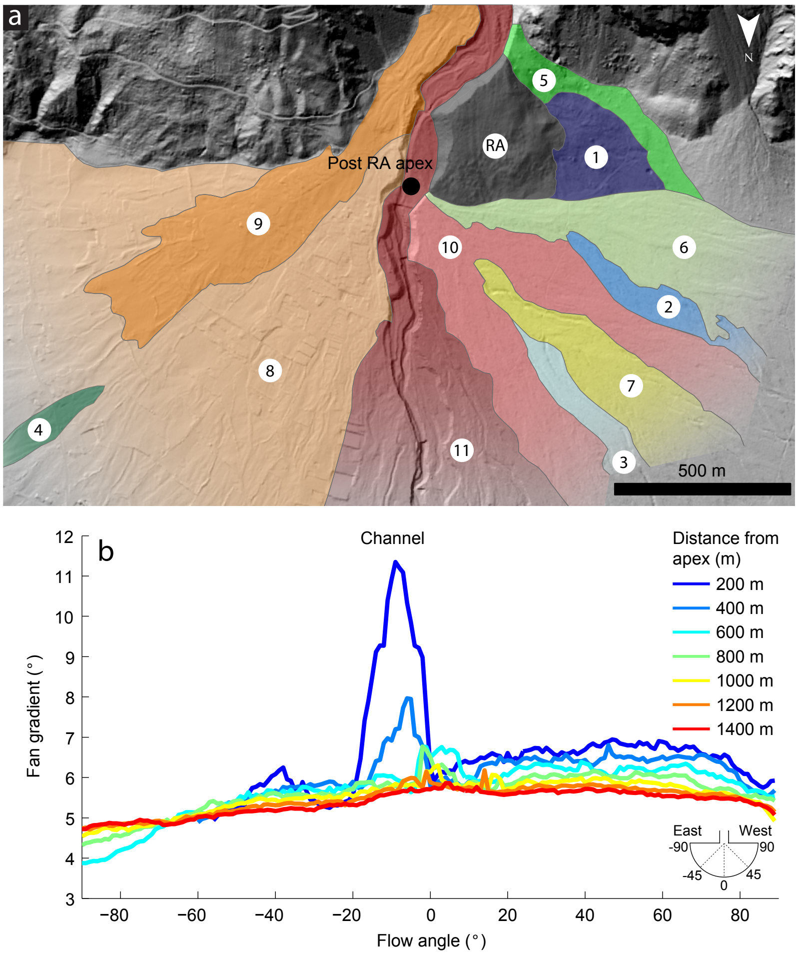

Figure 15: Spatio-temporal patterns of debris-flow activity on the Illgraben fan. (a) Chronology of distinct fan sectors on the Illgraben debris-flow fan as reconstructed by *Schürch et al.* [2016]. The sectors are numbered in decreasing order of depositional age. RA denotes a rock avalanche deposit, which was formed ~3200 yr BP. The emplacement of fan sectors 1 and 2 predate the rock avalanche, while sectors 5-11 postdate it. The relative chronology is based on mapping of debris-flow deposits with similar geomorphic signatures and crosscutting relationships between channels, together with ^{10}Be surface exposure dating of boulders [*Schürch et al.*, 2016]. (b) Average fan gradient for radial distances of 200-1400 m from the fan apex.

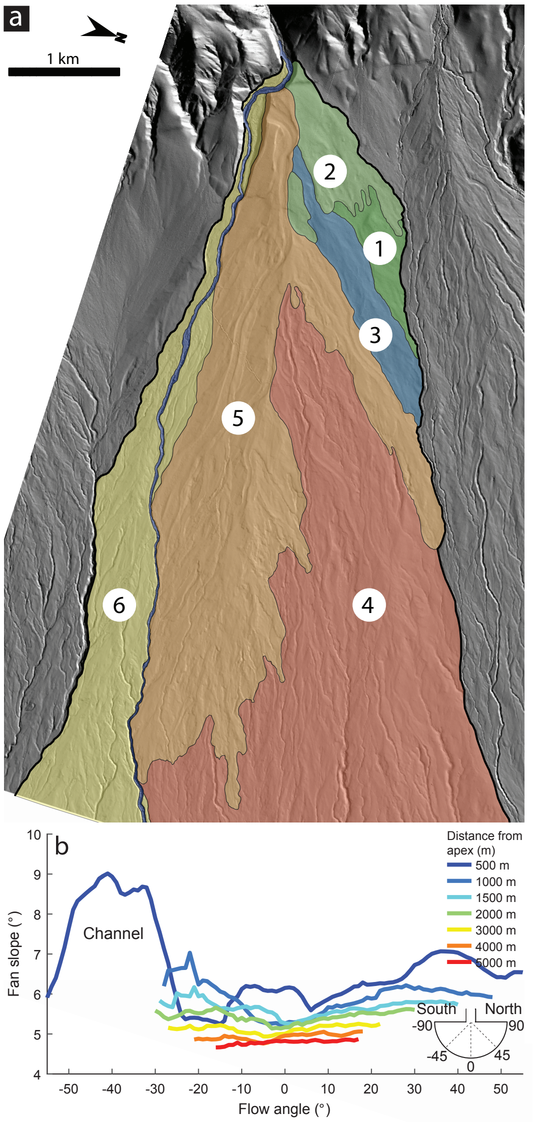

Figure 16: Spatio-temporal patterns of debris-flow activiy on the Shepherd Creek fan. (a) Chronology of fan deposition on the Shepherd Creek debris-flow fan as reconstructed by *Dühnforth et al.* [2007]. The sectors are numbered in decreasing order of formative age. Fan sector chronology is based on mapping of debris-flow deposits with similar geomorphic signatures, crosscutting relationships between channels and from ^{10}Be surface exposure dating of boulders by *Dühnforth et al.* [2007]. (b) Average fan gradient for radial distances of 500-5000 m from the fan apex.

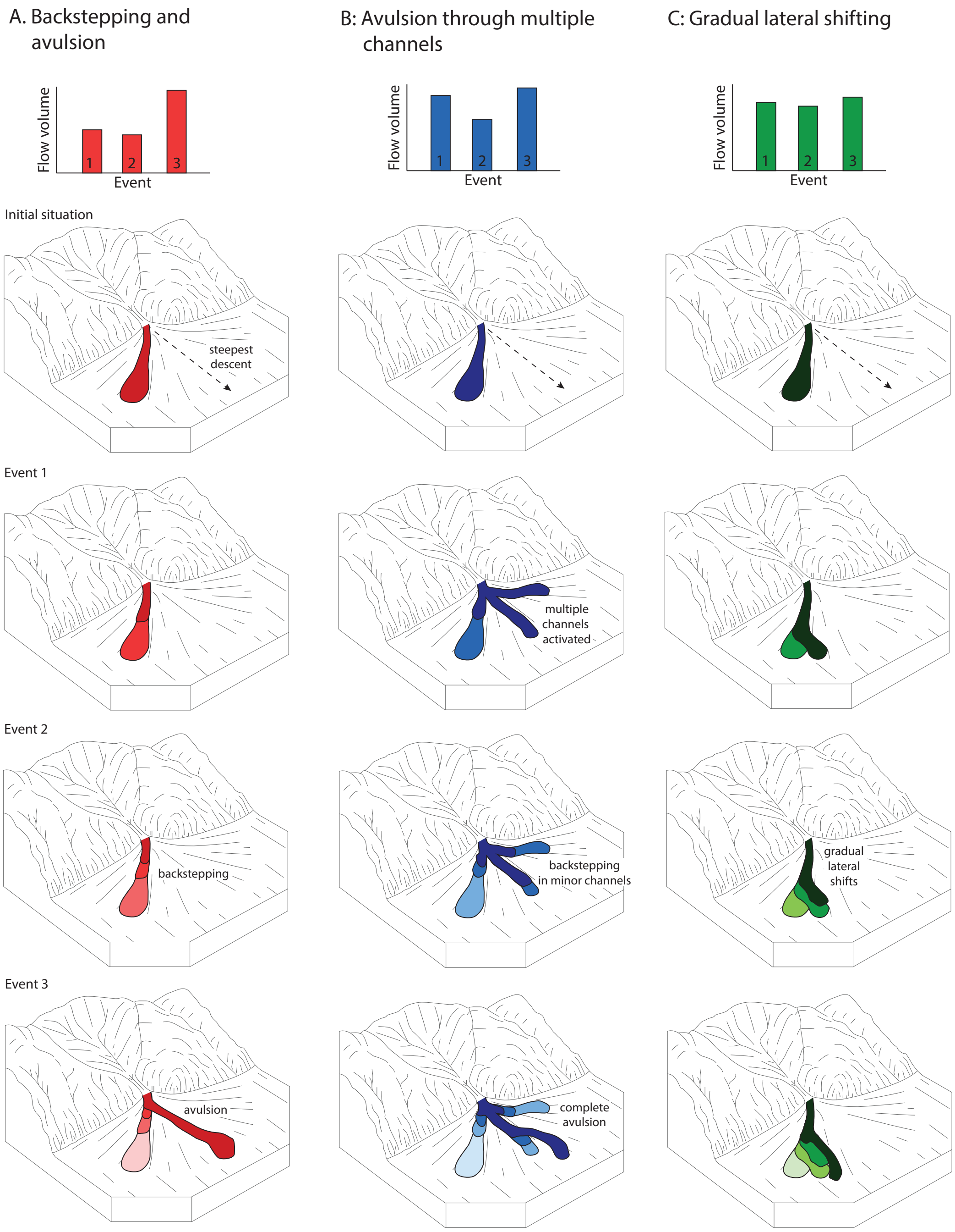

Figure 17: Conceptual diagram illustrating how varying flow volume sequences may lead to different avulsion patterns. Scenario A illustrates a typical backstepping and avulsion sequence, wherein channel plug deposition and backstepping occurs during small to moderate-sized flows followed by avulsion during a large flow. This sequence is typical for the Kamikamihori fan (Fig. 7). Scenario B illustrates how a large flow (event 1) can overtop the main channel to occupy and open (or close off) multiple channels. The most topographically favorable channel is enlarged in subsequent flows, while the other channels are closing off by plug deposition and backstepping. This sequence is typical for the Ohya and Ritigraben fans (Fig. 5, 8). Scenario C illustrates how flows can shift laterally towards a topographic depression on the fan, even during a sequence of similar-sized flows. Such a sequence can be observed on the Chalance and TCP-N1 fans (Figs 13, 14b).

Table 1: Fan characteristics. Ratio is defined as radial fan length divided by apex channel width. Climate is after the Köppen-Geiger climate classification in *Peel et al.* [2007]: Bsk = arid, cold steppe; Csb = temperate, dry and warm summer; Cfa = Temperate, without dry season, hot summer; Dfa = Cold, without dry season, hot summer; Dsa = cold, dry and hot summer; Dfb = cold, without dry season, warm summer; Dfc = cold, without dry season, cold summer; ET = Polar tundra.

Debris-flow fan	Country	Latitude	Longitude	Radial fan length (m)	Apex channel width (m)	Ratio	Fan area (m^2)	Fan slope °	Catchment area (m^2)	Catchment relief (m)	Climate zone	Age range	Events	Catchment lithology	Type	Source
Chalk Creek	USA	38.73	-106.17	40	6	7	2.46×10^3	7	2.8×10^5	470	Dfb	2009-2010	5	Quartz monzonite	Topographic	[*Wasklewicz and Scheinert*, 2016]
Ohya	Japan	35.31	138.31	600	7	86	6.54×10^4	18	2.3×10^5	420	Cfa	2006-2013	23	Sandstone, shale	Topographic	[*Imaizumi et al.*, 2016]
Kamikamihori	Japan	36.24	137.62	600	20	30	1.90×10^5	4.5	4.2×10^5	850	Dfa	1978-1999	12	Andesite, pyroclastic deposits, volcanic ash	Topographic	[*Suwa and Okuda*, 1983; *Suwa and Yamakoshi*, 1999]
Ritigraben	Switzerland	46.19	7.83	900	16	56	5.13×10^5	13	4.1×10^5	860	ET	1794-1993	34	Gneiss	Dendrogeomorphology	[*Stoffel et al.*, 2008; *Stoffel*, 2010]
Grosse Grabe	Switzerland	46.15	7.80	1000	35	29	4.31×10^5	20	9.6×10^5	1350	ET	1782-1993	35	Gneiss	Dendrogeomorphology	[*Bollschweiler et al.*, 2008]
Birchbach	Switzerland	46.12	7.79	550	20	28	1.87×10^5	13	7.5×10^6	2970	ET	1755-2000	46	Gneiss	Dendrogeomorphology	[*Bollschweiler and Stoffel*, 2010]
Bruchji	Switzerland	46.36	7.99	450	15	30	1.12×10^5	13	3.0×10^5	610	ET	1867-1996	41	Gneiss	Dendrogeomorphology	[*Bollschweiler et al.*, 2007]
Aksay	Kyrgyzstan	42.55	74.49	700	35	20	4.07×10^5	16	2.9×10^7	2520	Dsa	1877-1999	26	Granodiorites	Dendrogeomorphology	[*Zaginaev et al.*, 2016]
Chalance	France	44.82	6.21	600	20	30	3.68×10^5	21	1.1×10^6	1550	Dfc	1806-1996	14	Granite, Gneiss	Lichenometry	[*Helsen et al.*, 2002]
TCP	France	44.30	6.75	160	5	32	1.17×10^4	14	2.4×10^4	290	Csb	1928-1994	21	Limestone, sandstone, flysch and marls	Lichenometry/ dendrogeomorphology	[*Blijenberg*, 1998]
TCP-N1	France	44.31	6.75	150	5	30	8.67×10^3	12	2.4×10^4	270	Csb	1918-1994	20	Limestone, sandstone, flysch and marls	Lichenometry/ dendrogeomorphology	[*Blijenberg*, 1998]
TdP	France	44.29	6.75	450	8	56	6.67×10^4	25	6.9×10^4	440	Csb	1927-1972	10	Limestone, sandstone, flysch and marls	Lichenometry/ dendrogeomorphology	[*Blijenberg*, 1998]
TGE/TGW	France	44.32	6.77	100	10	10	8.09×10^3	18	1.1×10^5	450	Csb	1917-1971	14	Limestone, sandstone, flysch and marls	Lichenometry/ dendrogeomorphology	[*Blijenberg*, 1998]
Illgraben	Switzerland	46.30	7.63	2400	20	120	7.23×10^6	6	9.2×10^6	1850	ET	$\sim$2.2 ka - present	-	Limestone, quartzites, dolomite, schist	Cosmogenic nuclides	[*Schürch et al.*, 2016]
Shepherd creek	USA	36.72	-118.25	10000	80	125	$\sim3.00\times10^7$	4	3.4×10^7	2370	Bsk	$\sim$85 ka - 7 ka	-	Granite, granodiorite, monzonite	Cosmogenic nuclides	[*Dühnforth et al.*, 2007]

References

André, M.-F. (1990), Frequency of debris flows and slush avalanches in Spitsbergen: a tentative evaluation from lichenometry, *Polish Polar Research*, *11*, 345–363.

Arbellay, E., M. Stoffel, and M. Bollschweiler (2010), Dendrogeomorphic reconstruction of past debris-flow activity using injured broad-leaved trees, *Earth Surface Processes and Landforms*, *35*(4), 399–406.

Aslan, A., W. J. Autin, and M. D. Blum (2005), Causes of river avulsion: insights from the late Holocene avulsion history of the Mississippi River, USA, *Journal of Sedimentary Research*, *75*(4), 650–664.

Beaty, C. B. (1963), Origin of alluvial fans, White Mountains, California and Nevada, *Ann. Assoc. Am. Geogr.*, *53*(4), 516–535.

Berger, C., B. McArdell, and F. Schlunegger (2011), Direct measurement of channel erosion by debris flows, Illgraben, Switzerland, *Journal of Geophysical Research: Earth Surface (2003–2012)*, *116*, F01,002.

Blijenberg, H. (1998), Rolling Stones? Triggering and frequency of hillslope debris flows in the Bachelard Valley, southern French Alps, Ph.D. thesis, Universiteit Utrecht.

Bollschweiler, M., and M. Stoffel (2010), Variations in debris-flow occurrence in an Alpine catchmenta reconstruction based on tree rings, *Global and Planetary Change*, *73*(3), 186–192.

Bollschweiler, M., M. Stoffel, M. Ehmisch, and M. Monbaron (2007), Reconstructing spatio-temporal patterns of debris-flow activity using dendrogeomorphological methods, *Geomorphology*, *87*(4), 337–351.

Bollschweiler, M., M. Stoffel, and D. M. Schneuwly (2008), Dynamics in debris-flow activity on a forested cone - a case study using different dendroecological approaches, *Catena*, *72*(1), 67–78.

Bryant, M., P. Falk, and C. Paola (1995), Experimental study of avulsion frequency and rate of deposition, *Geology*, *23*(4), 365–368.

Cannon, S. H., J. E. Gartner, R. C. Wilson, J. C. Bowers, and J. L. Laber (2008), Storm rainfall conditions for floods and debris flows from recently burned areas in southwestern Colorado and southern California, *Geomorphology*, *96*(3), 250–269.

Cannon, S. H., E. M. Boldt, J. L. Laber, J. W. Kean, and D. M. Staley (2011), Rainfall intensity–duration thresholds for postfire debris-flow emergency-response planning, *Natural Hazards*, *59*(1), 209–236.

Carling, P., N. Gupta, P. Atkinson, and H. Q. He (2016), Criticality in the planform behavior of the Ganges River meanders, *Geology*, *44*(10), 859–862.

Cavalli, M., and L. Marchi (2008), Characterisation of the surface morphology of an alpine alluvial fan using airborne LiDAR, *Natural Hazards and Earth System Science*, *8*(2), 323–333.

Cesta, J. M., and D. J. Ward (2016), Timing and nature of alluvial fan development along the Chajnantor Plateau, northern Chile, *Geomorphology*, *273*, 412–427.

Chamberlin, E., E. Hajek, and S. Trampush (2016), Measuring scales of autogenic organization in fluvial stratigraphy: An example from the Cretaceous Lower Williams Fork Formation, Colorado, *Autogenic Dynamics in Sedimentary Systems: SEPM (Society for Sedimentary Geology) Special Publication*, *106*.

Clague, J. J., C. Huggel, O. Korup, and B. McGuire (2012), Climate change and hazardous processes in high mountain, *Revista de la Asociación Geológica Argentina*, *69*(3), 328–338.

Clarke, L., T. A. Quine, and A. Nicholas (2010), An experimental investigation of autogenic behaviour during alluvial fan evolution, *Geomorphology*, *115*(3), 278–285.

Costa, J. E. (1988), Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows, *Flood Geomorphology*, pp. 113–122.

De Haas, T., and T. Van Woerkom (2016), Bed scour by debris flows: experimental investigation of effects of debris-flow composition, *Earth Surface Processes and Landforms*, *41*(13), 1951–1966, doi:10.1002/esp.3963, esp.3963.

De Haas, T., D. Ventra, P. E. Carbonneau, and M. G. Kleinhans (2014), Debris-flow dominance of alluvial fans masked by runoff reworking and weathering, *Geomorphology*, *217*, 165–181.

De Haas, T., M. G. Kleinhans, P. E. Carbonneau, L. Rubensdotter, and E. Hauber (2015a), Surface morphology of fans in the high-Arctic periglacial environment of Svalbard: Controls and processes, *Earth-Science Reviews*, *146*, 163–182.

De Haas, T., L. Braat, J. F. W. Leuven, I. R. Lokhorst, and M. G. Kleinhans (2015b), Effects of debris-flow composition and topography on runout distance, depositional mechanisms and deposit morphology, *Journal of Geophysical Research: Earth Surface*, *120*, 1949–1972.

De Haas, T., E. Hauber, S. J. Conway, H. van Steijn, A. Johnsson, and M. G. Kleinhans (2015b), Earth-like aqueous debris-flow activity on Mars at high orbital obliquity in the last million years, *Nature Communications*, *6:7543*.

De Haas, T., W. Berg, L. Braat, and M. G. Kleinhans (2016), Autogenic avulsion, channelization and backfilling dynamics of debris-flow fans, *Sedimentology*, *63*, 1596–1619.

Dowling, C. A., and P. M. Santi (2014), Debris flows and their toll on human life: a global analysis of debris-flow fatalities from 1950 to 2011, *Natural hazards*, *71*(1), 203–227.

Dühnforth, M., A. L. Densmore, S. Ivy-Ochs, P. A. Allen, and P. W. Kubik (2007), Timing and patterns of debris flow deposition on Shepherd and Symmes creek fans, Owens Valley, California, deduced from cosmogenic 10Be, *Journal of Geophysical Research: Earth Surface (2003–2012)*, *112*(F3).

Dühnforth, M., A. L. Densmore, S. Ivy-Ochs, and P. A. Allen (2008), Controls on sediment evacuation from glacially modified and unmodified catchments in the eastern Sierra Nevada, California, *Earth Surface Processes and Landforms*, *33*(10), 1602–1613.

Dühnforth, M., A. L. Densmore, S. Ivy-Ochs, P. Allen, and P. W. Kubik (2017), Early to Late Pleistocene history of debris-flow fan evolution in western Death Valley (California) using cosmogenic 10 Be and 26 Al, *Geomorphology*, *281*, 53–65.

Edmonds, D. A., E. A. Hajek, N. Downton, and A. B. Bryk (2016), Avulsion flow-path selection on rivers in foreland basins, *Geology*, *44*(9), 695–698.

Frank, F., B. McArdell, C. Huggel, and A. Vieli (2015), The importance of erosion for debris flow runout modelling from applications to the swiss alps, *Natural Hazards and Earth System Sciences Discussions*, *3*, 2379–2417.

Frankel, K. L., and J. F. Dolan (2007), Characterizing arid region alluvial fan surface roughness with airborne laser swath mapping digital topographic data, *J. Geophys. Res.*, *112*, F02,025.

Hajek, E. A., P. L. Heller, and B. A. Sheets (2010), Significance of channel-belt clustering in alluvial basins, *Geology*, *38*(6), 535–538.

Helsen, M. M., P. J. M. Koop, and H. Van Steijn (2002), Magnitude-frequency relationship for debris flows on the fan of the Chalance torrent, Valgaudemar (French Alps), *Earth Surface Processes and Landforms*, *27*(12), 1299–1307.

Hooke, R. L. (1967), Processes on arid-region alluvial fans, *The Journal of Geology*, pp. 438–460.

Hoyal, D., and B. Sheets (2009), Morphodynamic evolution of experimental cohesive deltas, *Journal of Geophysical Research: Earth Surface (2003–2012)*, *114*(F2).

Huang, R., and X. Fan (2013), The landslide story, *Nature Geoscience*, *6*(5), 325–326.

Imaizumi, F., and S. Tsuchiya (2008), Debris-Flow Behaviors in a Steep Mountainous Torrent on Ohya Landslide, Japan, in *Proceedings 4th International Conference on Scour and Erosion (ICSE-4). November 5-7, 2008, Tokyo, Japan*, pp. 665–671.

Imaizumi, F., S. Tsuchiya, and O. Ohsaka (2005), Behaviour of debris flows located in a mountainous torrent on the Ohya landslide, Japan, *Canadian Geotechnical Journal*, *42*(3), 919–931.

Imaizumi, F., D. Trappmann, N. Matsuoka, S. Tsuchiya, O. Ohsaka, and M. Stoffel (2016), Biographical sketch of a giant: Deciphering recent debris-flow dynamics from the Ohya landslide body (Japanese Alps), *Geomorphology*, *272*, 102–114.

Imaizumi, F., Y. Hayakawa, N. Hotta, H. Tsunetaka, O. Ohsaka, and S. Tsuchiya (2017), Relationship between the accumulation of sediment storage and debris flow characteristics in a debris-flow initiation zone, Ohya landslide body, Japan, *Natural Hazards and Earth System Sciences*, pp. 1–26, doi:10.5194/nhess-2017-20.

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

Iverson, R. M. (2012), Elementary theory of bed-sediment entrainment by debris flows and avalanches, *Journal of Geophysical Research: Earth Surface*, *117*(F3).

Iverson, R. M. (2014), Debris flows: behaviour and hazard assessment, *Geology Today*, *30*(1), 15–20.

Iverson, R. M., M. E. Reid, M. Logan, R. G. LaHusen, J. W. Godt, and J. P. Griswold (2011), Positive feedback and momentum growth during debris-flow entrainment of wet bed sediment, *Nature Geoscience*, *4*(2), 116–121.

Jakob, M., and P. Friele (2010), Frequency and magnitude of debris flows on cheekye river, british columbia, *Geomorphology*, *114*(3), 382–395.

Jerolmack, D. J., and D. Mohrig (2007), Conditions for branching in depositional rivers, *Geology*, *35*(5), 463–466.

Jerolmack, D. J., and C. Paola (2007), Complexity in a cellular model of river avulsion, *Geomorphology*, *91*(3), 259–270.

Ma, C., Y. Wang, K. Hu, C. Du, and W. Yang (2017), Rainfall intensity–duration threshold and erosion competence of debris flows in four areas affected by the 2008

Wenchuan earthquake, *Geomorphology*, *282*, 85–95.

Major, J. J., and R. M. Iverson (1999), Debris-flow deposition: Effects of pore-fluid pressure and friction concentrated at flow margins, *Geological Society of America Bulletin*, *111*(10), 1424–1434.

McCoy, S., J. Kean, J. Coe, G. Tucker, D. Staley, and T. Wasklewicz (2012), Sediment entrainment by debris flows: In situ measurements from the headwaters of a steep catchment, *Journal of Geophysical Research: Earth Surface (2003–2012)*, *117*(F3).

McCoy, S. W., J. W. Kean, J. A. Coe, D. M. Staley, T. A. Wasklewicz, and G. E. Tucker (2010), Evolution of a natural debris flow: In situ measurements of flow dynamics, video imagery, and terrestrial laser scanning, *Geology*, *38*(8), 735–738.

McCoy, S. W., J. A. Coe, J. W. Kean, G. E. Tucker, D. M. Staley, and T. A. Wasklewicz (2011), Observations of debris flows at Chalk Cliffs, Colorado, USA: Part 1, in-situ measurements of flow dynamics, tracer particle movement, and video imagery from the summer of 2009, *Italian Journal of Engineering Geology and Environment*, *1*(11), 67–75.

Mohrig, D., P. L. Heller, C. Paola, and W. J. Lyons (2000), Interpreting avulsion process from ancient alluvial sequences: Guadalope-matarranya system (northern spain) and wasatch formation (western colorado), *Geological Society of America Bulletin*, *112*(12), 1787–1803.

Okano, K., H. Suwa, and T. Kanno (2012), Characterization of debris flows by rainstorm condition at a torrent on the Mount Yakedake volcano, Japan, *Geomorphology*, *136*(1), 88–94.

Okuda, S., S. Suwa, K. Okunishi, and K. Yokoyama (1981), Depositional processes of debris flow at Kamikamihori fan, Northern Japan Alps, *Trans. Japan. Geomorph. Union*, *2*, 353–361.

Owen, L. A., S. J. Clemmens, R. C. Finkel, and H. Gray (2014), Late Quaternary alluvial fans at the eastern end of the San Bernardino Mountains, Southern California, *Quaternary Science Reviews*, *87*, 114–134.

Pederson, C. A., P. M. Santi, and D. R. Pyles (2015), Relating the compensational stacking of debris-flow fans to characteristics of their underlying stratigraphy: Implications for geologic hazard assessment and mitigation, *Geomorphology*, *248*, 47–56.

Peel, M. C., B. L. Finlayson, and T. A. McMahon (2007), Updated world map of the köppen-geiger climate classification, *Hydrology and earth system sciences discussions*, *4*(2), 439–473.

Procter, E., M. Stoffel, M. Schneuwly-Bollschweiler, and M. Neumann (2012), Exploring debris-flow history and process dynamics using an integrative approach on a dolomitic cone in western Austria, *Earth surface processes and landforms*, *37*(9), 913–922.

Pudasaini, S. P. (2012), A general two-phase debris flow model, *Journal of Geophysical Research: Earth Surface (2003–2012)*, *117*(F3).

Reitz, M. D., and D. J. Jerolmack (2012), Experimental alluvial fan evolution: Channel dynamics, slope controls, and shoreline growth, *Journal of Geophysical Research: Earth Surface*, *117*(F2), F02,021.

Reitz, M. D., D. J. Jerolmack, and J. B. Swenson (2010), Flooding and flow path selection on alluvial fans and deltas, *Geophysical Research Letters*, *37*(6), L06,401.

Schneuwly-Bollschweiler, M., and M. Stoffel (2012), Hydrometeorological triggers of periglacial debris flows in the Zermatt valley (Switzerland) since 1864, *Journal of Geophysical Research: Earth Surface*, *117*, F02,033.

Schneuwly-Bollschweiler, M., C. Corona, and M. Stoffel (2013), How to improve dating quality and reduce noise in tree-ring based debris-flow reconstructions, *Quaternary Geochronology*, *18*, 110–118.

Schumm, S., M. Mosley, and W. Weaver (1987), *Experimental Fluvial Geomorphology*, John Wiley and Sons, New York.

Schürch, P., A. L. Densmore, N. J. Rosser, and B. W. McArdell (2011), Dynamic controls on erosion and deposition on debris-flow fans, *Geology*, *39*(9), 827–830.

Schürch, P., A. L. Densmore, S. Ivy-Ochs, N. J. Rosser, F. Kober, F. Schlunegger, B. McArdell, and V. Alfimov (2016), Quantitative reconstruction of late Holocene surface evolution on an alpine debris-flow fan, *Geomorphology*, *275*, 46–57.

Sheets, B. A., C. Paola, and J. M. Kelberer (2007), Creation and preservation of channel-form sand bodies in an experimental alluvial system, *Sedimentary processes, environments and basins: a tribute to Peter Friend*, pp. 555–567.

Shieh, C.-L., Y. Chen, Y. Tsai, and J. Wu (2009), Variability in rainfall threshold for debris flow after the Chi-Chi earthquake in central Taiwan, China, *International Journal of Sediment Research*, *24*(2), 177–188.

Stoffel, M. (2010), Magnitude–frequency relationships of debris flows-a case study based on field surveys and tree-ring records, *Geomorphology*, *116*(1), 67–76.

Stoffel, M., and M. Beniston (2006), On the incidence of debris flows from the early Little Ice Age to a future greenhouse climate: a case study from the Swiss Alps, *Geo-*

physical Research Letters, *33*(16), doi:10.1029/2006GL026805.

Stoffel, M., and M. Bollschweiler (2009), What tree rings can tell about earth-surface processes: Teaching the principles of dendrogeomorphology, *Geography Compass*, *3*(3), 1013–1037.

Stoffel, M., I. Lièvre, D. Conus, M. A. Grichting, H. Raetzo, H. W. Gärtner, and M. Monbaron (2005), 400 years of debris-flow activity and triggering weather conditions: Ritigraben, Valais, Switzerland, *Arctic, Antarctic, and Alpine Research*, *37*(3), 387–395.

Stoffel, M., D. Conus, M. A. Grichting, I. Lièvre, and G. Maître (2008), Unraveling the patterns of late Holocene debris-flow activity on a cone in the Swiss Alps: chronology, environment and implications for the future, *Global and Planetary Change*, *60*(3), 222–234.

Stoffel, M., T. Mendlik, M. Schneuwly-Bollschweiler, and A. Gobiet (2014), Possible impacts of climate change on debris-flow activity in the Swiss Alps, *Climatic Change*, *122*, 141–155.

Straub, K. M., and D. R. Pyles (2012), Quantifying the hierarchical organization of compensation in submarine fans using surface statistics, *Journal of Sedimentary Research*, *82*(11), 889–898.

Straub, K. M., C. Paola, D. Mohrig, M. A. Wolinsky, and T. George (2009), Compensational stacking of channelized sedimentary deposits, *Journal of Sedimentary Research*, *79*(9), 673–688.

Suwa, H. (1988), Focusing mechanism of large boulders to a debris-flow front, *Transactions of the Japanese Geomorphological Union*, *9*, 151–178.

Suwa, H. (2003), Repetition of debris flows on sunny days at a torrent in Karakorum, in *Proc. 3rd Inter. Conf. on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment: Rikkenmann, D. and Wieczorek, G. (eds.)*, Balkema.

Suwa, H. (2017), Pulsation in debris flows and its mechanism, *International Journal of Erosion Control Engineering*, *10*, 16–23.

Suwa, H., and S. Okuda (1983), Deposition of debris flows on a fan surface, Mt. Yakedake, Japan, *Zeitschrift fur Geomorphologie NF Supplementband*, *46*, 79–101.

Suwa, H., and T. Yamakoshi (1999), Sediment discharge by storm runoff at volcanic torrents affected by eruption, *Zeitschrift fur Geomorphologie NF Supplementband*, *114*, 63–88.

Suwa, H., K. Okano, and T. Kanno (2009), Behavior of debris flows monitored on test slopes of Kamikamihorizawa Creek, Mount Yakedake, Japan, *International Journal of Erosion Control Engineering*, *2*(2), 33–45.

Suwa, H., T. Okano, and T. Kanno (2011), *5th International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction and Assessment*, chap. Forty years of debris-flow monitoring at Kamikamihorizawa Creek, Mount Yakedake, Japan, pp. 605–613, Casa Editrice Universita La Sapienza, Roma.

Takahashi, T. (1978), Mechanical aspects of debris flow, *American Society of Civil Engineers Proceedings, Journal of the Hydraulics Division*, *104*, 1153–1169.

Tsuchiya, S., F. Imaizumi, S. Ikeda, S. Egashira, T. Mizuyama, et al. (2010), Large sediment movement caused by the catastrophic Ohya-kuzure landslide, *Journal of Disaster Research*, *5*(3), 257–263.

Van Dijk, M., G. Postma, and M. G. Kleinhans (2009), Autocyclic behaviour of fan deltas: an analogue experimental study, *Sedimentology*, *56*(5), 1569–1589.

Van Dijk, M., M. G. Kleinhans, G. Postma, and E. Kraal (2012), Contrasting morphodynamics in alluvial fans and fan deltas: effect of the downstream boundary, *Sedimentology*, *59*(7), 2125–2145.

Van Dijk, W., A. Densmore, A. Singh, S. Gupta, R. Sinha, P. Mason, S. Joshi, N. Nayak, M. Kumar, S. Shekhar, et al. (2016), Linking the morphology of fluvial fan systems to aquifer stratigraphy in the Sutlej-Yamuna plain of northwest India, *Journal of Geophysical Research: Earth Surface*, *121,*, 201–222.

Van Steijn, H. (1996), Debris-flow magnitude-frequency relationships for mountainous regions of central and northwest europe, *Geomorphology*, *15*(3), 259–273.

Ventra, D., and G. J. Nichols (2014), Autogenic dynamics of alluvial fans in endorheic basins: Outcrop examples and stratigraphic significance, *Sedimentology*, *61*(3), 767–791.

Wang, Y., K. M. Straub, and E. A. Hajek (2011), Scale-dependent compensational stacking: an estimate of autogenic time scales in channelized sedimentary deposits, *Geology*, *39*(9), 811–814.

Wasklewicz, T., and C. Scheinert (2016), Development and maintenance of a telescoping debris flow fan in response to human-induced fan surface channelization, Chalk Creek Valley Natural Debris Flow Laboratory, Colorado, USA, *Geomorphology*, *252*, 51–65.

Whipple, K. X., and T. Dunne (1992), The influence of debris-flow rheology on fan morphology, Owens Valley, California, *Geological Society of America Bulletin*, *104*(7), 887–900.

Whipple, K. X., G. Parker, C. Paola, and D. Mohrig (1998), Channel dynamics, sediment transport, and the slope of alluvial fans: experimental study, *The Journal of Geology*, *106*(6), 677–694.

Wieczorek, G. F., M. Larsen, L. Eaton, B. Morgan, and J. Blair (2001), Debris-flow and flooding hazards associated with the december 1999 storm in coastal venezuela and strategies for mitigation, *Tech. Rep. (Open File Report 01-0144)*, US Geological Survey.

Zaginaev, V., J. Ballesteros-Cánovas, S. Erokhin, E. Matov, D. Petrakov, and M. Stoffel (2016), Reconstruction of glacial lake outburst floods in northern Tien Shan: Implications for hazard assessment, *Geomorphology*, *269*, 75–84.

Zehfuss, P. H., P. R. Bierman, A. R. Gillespie, R. M. Burke, and M. W. Caffee (2001), Slip rates on the fish springs fault, owens valley, california, deduced from cosmogenic 10be and 26al and soil development on fan surfaces, *Geological Society of America Bulletin*, *113*(2), 241–255.

Zimmermann, M. (1991), Formation of debris flow cones: results from model tests, in *Proceedings of the US-Japan Symposium of Snow Avalanche, Landslide Debris-Flow Prediction and Control*, pp. 463–470.