Debris flows that are confined by canyons generally exhibit distributary behavior once they exit the canyons, usually creating some sort of debris fan. This distributary nature is commonly observed in fluvial processes, as avulsion out of established flow paths allows the system to methodically fill topographic lows and develop regular, fan-shaped deposits. For debris flows, avulsion represents a serious hazard, because future debris flows may occur in areas that have not experienced events in the recent past, and flows may occur at significant distances across the fan away from currently active channels. It is important to be able to identify avulsion-susceptible areas, to quantify the likelihood of avulsion, and to model and mitigate the possibility of avulsion. Map views of several debris fans showing locations of successive events were analyzed to evaluate the degree of avulsion. In addition, cross-fan sections at three locations in Colorado were interpreted stratigraphically and analyzed to calculate a modified compensation index, $K_{cv}$, a single number that indicates significant avulsion activity ($K_{cv}$ near one), or low avulsion activity ($K_{cv}$ near 0.5). Areas with typical debris-flow characteristics (abundant coarse clasts, thick units, large lobes, high clay content) tended to have higher compensation indices than areas with typical stream-flow characteristics (thinner, with less clay and coarse clasts). Finally, several sites are reviewed where an understanding of avulsion could help anticipate flow behavior and direct mitigation efforts.

**Key words:** debris flows, avulsion, debris fan, deposits, hazard

1. **INTRODUCTION**

Not only are the timing and magnitude of debris flows difficult to predict, but the path followed by a flow can vary across a debris fan or within a valley. The abundance of coarse clasts and large woody debris causes frequent damming of flow paths and avulsion to new areas. This erratic behavior extends the potential hazard across wide areas. For example, a 2002 debris flow on the Stevens Creek fan near Durango, Colorado (Fig. 1) clogged the main flow channel and avulsed across the fan, over 60 m away, inundating a house in an unexpected area [Coe et al., 2007]. A better understanding of avulsion behavior, and particularly a quantification of the process, will be valuable in assessing and reducing debris-flow hazards.

2. **PURPOSE**

The purpose of this research is to explore ways of identifying and quantifying debris-flow avulsion, with the eventual aim of answering two questions: can we predict the likelihood of avulsion in a given setting, and how would such a prediction inform our mitigation plans?
We will start by exploring avulsion from map views of several debris fans, followed by avulsion analysis of cross-fan exposures. Finally, a few brief case studies will be discussed to illustrate the implications of debris-flow avulsion.

3. AVULSION ANALYSIS FROM MAP VIEWS

Three issues related to avulsion can be considered from map views of debris fans and other debris-flow runout areas; namely, the progression of active deposition across the fan, the area covered by typical flow events, and the branching nature of individual flows.

The progression of active deposition is shown by Bollschweiler et al. [2007], who used 960 tree ring growth disturbances to identify 40 different debris-flow events over the period 1867 to 2005 on the Bruchji fan in the Swiss Alps. They divided the events based on the predominant area of the fan flooded (Fig. 2). Plotting these groups (Fig. 3) shows a qualitative progression of flows from the western part of the fan to the eastern part (with several notable exceptions). Figure 3 also shows a comparable, if less detailed, result for the Ritigraben fan, also in the Swiss Alps and mapped by Stoffel [2011] (Fig. 4). Specific dates for individual lobes are given in the original references. These results support the general logic that sections of the fan build through deposition over several events before avulsing to other sections that are topographically lower. From a hazards standpoint, this means that successive events are frequently in the same sector, with gradual shifting to other parts of the fan, but with occasional events in unexpected locations.

The area of the fan impacted by a single event is also a direct indicator of the degree of hazard imposed by flow events. Debris flows confined to channel-like paths are less likely to impact structures than flows that spread across wide sectors of the fan. For example, five events on the Bruchji fan were plotted on Fig. 5, showing the percent width of the fan (measured from detailed figures in the original reference) impacted in each event at the apex, medial and distal portions of the fan. Most events impact a large width of the fan at the apex, where the fan is restricted to a narrow throat, with less impact at medial and distal locations, where the fan is broad. An exception is the 1962 event, which affected nearly the entire cone, and the 1919 event, which affected a small but increasing area downfan. Figure 6 shows a similar pattern for a single event on the Oak Creek fan in California [Wagner et al., 2012], with a narrower impacted area downfan.
Fig. 4 Debris flow lobes dated by tree ring analysis at the Ritigraben fan, Switzerland (from Stoffel [2011], used by permission).

Fig. 5 Bruchji fan, percent width of debris flow of total fan width plotted against location on fan (0 = proximal, 0.5 = medial, 1 = distal). Measurements collected from flow maps in Bollschweiler [2007].

The maps of the Bruchji fan in Fig. 2 and the Ritigraben fan in Fig. 4 also demonstrate the importance of the branching nature of debris flows, caused by blockages that divert part of the material into numerous lobes. Fans that typically develop narrow flow events can become much more hazardous if the flows tend to follow multiple paths.

In summary, debris-flow hazards cannot be judged simply: one must consider avulsion and potential sweeping of the active deposition area across the fan, the volume and related extent of impacts, and the branching or splitting of flows that would affect additional areas.

4. AVULSION ANALYSIS FROM CROSS-SECTIONS

Straub et al. [2009] and Straub and Pyles [2012] used mathematical analysis to quantify evolution and avulsion tendencies of outcrop exposures of deep-water, fluvial, and deltaic fan systems. They developed and refined a “modified
compensation index,” $K_{cv}$, that measures the degree of compensational stacking, which is the tendency of successive deposits to fill topographic lows before avulsion causes a channel to migrate to another part of the sediment transport field. Specifically, they evaluated the coefficient of variation ($CV$) as a function of the ratio of local to mean sediment thicknesses between every pairwise combination of unit contacts mapped in outcrop, integrated across the length ($L$) of an exposed outcrop [Pederson, 2014]. Values range from anti-compensational (0.0), to uncorrelated or intermediate (0.5), to perfectly compensational (1.0) [Straub et al., 2009]. In avulsion terms, anti-compensational and intermediate fans tend to build in place with fewer avulsions, and highly compensational fans experience frequent avulsion, as successive events jump frequently to new topographic lows.

Pederson [2014] mapped and calculated modified compensation indices for debris fans using these techniques. Cross-fan exposures had been created by road cuts or landslide scarps at three sites in Colorado, near Grand Mesa (referred to as “Cedar Mesa”), Poncha Pass (Fig. 7), and Woodland Park. For these sites he calculated $K_{cv}$ values of 1.03 for Cedar Mesa (highly compensational), 0.80 to 1.01 for Poncha Pass (the range of values representing end-member interpretations of eroded boundaries on one side of the fan), and 0.63 for Woodland Park (intermediate compensational).
Although there were only three sites evaluated, the incorporation of grain size analysis and geomorphic and stratigraphic information allowed some general trends to be identified, shown on Fig. 8. These trends indicate that areas with typical debris-flow characteristics (abundant coarse clasts, thick units, large lobes, high clay content) tended to be more compensational than areas with typical stream-flow characteristics (thinner, with less clay and coarse clasts).

This analytical tool shows strong promise for debris-flow avulsion analysis, and we are currently identifying additional cross-fan exposures for evaluation, measuring the relation between $K_c$ and distance from fan apex with flume runout experiments, and developing methodology to use drill hole data to measure $K_c$.

5. CASE STUDIES

5.1 Stevens Creek fan, Durango, Colorado

The Stevens Creek area, located 12 km north of Durango, Colorado, was burned by the Missionary Ridge wildfire during the summer of 2002, then impacted by several debris flows in September 2002. As noted earlier, these flows induced migration of the active channel, and there is evidence on the fan that “channels were blocked by large boulders and diverted many times during the event” [Coe et al., 2007]. Some evidence of this can be seen in Fig. 9, in the faint tracks of distributary channels near the road. These channels are developed sequentially, and not simultaneously. The idea of sequential channel development of a fan, as opposed to a braided, distributary structure where large sectors are constructed at one time, matches the observations of Blair and McPherson [2009], who emphasize the importance of debris-flow and sheet flood deposits in the construction of alluvial fans.

The likelihood of avulsion on the Stevens Creek fan is reflected in the radial shape of the fan as the channel leaves the confinement of the upstream gorge (Fig. 9), and in the surface levees and boulder trains indicating previous debris-flow paths. Avulsion can be reduced somewhat by channelization of the flow through excavation and construction of man-made levees like those seen in Fig. 1. However, channelized flows can still dam and avulse, depending on the velocity change as the flow passes the fan apex, the size of material in an individual event, and the discharge rate.

5.2 Unnamed drainage, Provo, Utah

Following the Mollie Fire in 2002, a small debris flow occurred near Provo, Utah in the spring of 2003. Figure 10 shows the rocky, levee-bounded splitting channels created during the flow. This near-simultaneous distributary pattern is in contrast to the previous example, and is probably reflective of the small scale of the feature. In this case, it is likely that a temporary in-channel dam caused the split and avulsion, but the dam was breached later in the event. The fluid tail of the debris flow and subsequent runoff continued to deepen the channels to the current configuration.
Fig. 11 Cable Canyon fan near San Bernardino, California (from Google Earth, 6/7/2012 image date). Fatalities occurred in proximal fan area where W. Myers Rd. intersects the valley. Note fresh deposits on right medial and distal end of fan.

Fig. 12 Debris flow deposits in proximal fan area at Cable Canyon. Several levee-bounded debris trains covered the entire 200 m width of the canyon.

5.3 Cable Canyon, San Bernardino, California

A debris flow in Cable Canyon on Christmas Day 2003, following the 2003 Old Fire, killed three people and inundated a campground near the apex of the fan. Figure 11 shows the configuration of the fan and Fig. 12 shows the nature of the deposits. Because the campground was located in the semi-confined upper portion of the fan, nearly the entire 200 m width of the canyon was impacted by multiple, levee-lined debris-flow channels. This case is similar to the fans in Figs. 2 and 4, where the hazard is much higher in the proximal part of the fan than in the medial or distal parts.

5.4 Santa Barbara, California

McCoy et al. [2014] predicted debris-flow probability, volume, runout, and damage near Santa Barbara, California that could result following the 2009 Jesusita Fire. Using GIS tools, databases of property values, and estimates of mitigation costs, they derived a curve of estimated damage resulting from debris flows of different sizes (Fig. 13). The shape of this curve is significant: once the debris flow reaches a certain magnitude, it overflows its active channel and impacts a much larger area, shown by the rapidly escalating costs at a magnitude of approximately 400,000 m$^3$. Even without a complete avulsion, the loss of
confinement of a flow is the first step towards avulsion and it can dramatically increase the hazard and associated damages.

6. CONCLUSIONS

Avulsion of debris flows is an unpredictable process that greatly amplifies the potential hazards and expands the areas at risk. The nature of a specific debris fan can be better understood through historic analysis of debris-flow paths and active channel migration, by evaluation of branching nature and typical flow widths at different parts of the fan, and by quantitative analysis of stratigraphic compensation. Specific cases demonstrate the importance of these analyses, as well as the variability of behavior that necessitates site-specific studies.

The variability of responses, even with the small datasets used in this study, reflects the need for continued work in this area. Furthermore, numerous other factors play into debris-flow avulsion that were not included here, such as the influence of drainage basin and debris fan size, the effects of the fan slope and the change in slope at the apex, the nature and geology of the source materials, and the changing composition of debris-flow materials downfan as boulders and coarse materials are preferentially deposited in proximal areas.

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