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A NOVEL DEBRIS-FLOW FAN EVOLUTION MODEL BASED ON DEBRIS FLOW MONITORING AND LIDAR TOPOGRAPHY

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ABSTRACT

In this paper we present the rationale for a new approach to the modelling of debris-flow fans. Understanding debris-flow fan evolution is important for two reasons: fans are potential archives of past environmental conditions of mountain belts, and they are commonly inhabited despite the threat of debris flow occurrence. There are currently no models available that adequately represent debris flows as agents of geomorphic landscape change over the time scales (10^3 to 10^6 y) necessary to construct fans, which severely limits our ability to understand both short- and long-term fan behaviour. We describe in detail how results from debris flow monitoring, LiDAR topography and geomorphic mapping of debris flow fans, together with empirical relationships on debris flow behaviour, can be used to inform a novel debris-flow fan evolution model. The model we propose will be useful for both the analysis of long-term fan evolution and hazard analysis over short to medium time scales.

Key words: debris flow, fan evolution, modelling, erosion, deposition

INTRODUCTION

Understanding debris-flow fan evolution is important for two main reasons. First, debris-flow fans are potentially valuable archives of past environmental conditions of mountain belts and associated channel systems (Dühnforth *et alii*, 2007, Densmore *et alii*, 2007). Reading this archive, however, requires a quantitative understanding of both how debris-flow fans are built up over time, and how their deposits and surface morphology can be altered by post-depositional processes. Second, debris-flow fans form valuable low-gradient surfaces that are commonly used for agriculture or human habitation in mountainous areas, despite the threat of flow inundation. Debris flow hazard assessment usually involves modelling the effect of single flows (of a specific volume) on the present day topography. Dalbey *et alii* (2008) pointed out that traditional debris flow hazard assessment often ignores the effects of uncertainties in the input parameters (flow parameters and topography) on the output (hazard assessment). To our knowledge no attempt has been made to quantify the uncertainty in the hazard assessment due to the evolution (i.e. incision, aggradation, avulsion) of the channel system over a sequence of events.

Both the (unknown) interactions between process and developing form on debris-flow fans, and the effects of channel evolution over the course of multiple events on hazard assessment, can be investigated through a quantitative model of fan evolution over geological (10^3 to 10^6 y) time scales. Such a model must explicitly incorporate the complex interactions between debris flows and the surface topography but must also be efficient enough to allow multiple simulations over long time scales. In this paper we review the conceptual basis for a novel modelling approach that clarifies the long-term effect of debris-flow-specific patterns of erosion and deposition on the evolution of debris-flow fan morphology.

REVIEW OF FAN AND DEBRIS FLOW MODELS

In this section we review the concepts of existing numeric fan evolution and debris flow models. A first class of models has been developed to examine the filling of accommodation over geological time scales by sediment which is transported by fluvial processes. Such alluvial fan or fan-delta models are commonly based on general formulations of sediment transport and flow resistance that average deposition in space and time (Parker *et alii*, 1998; De Chant, 1999). For example, in the model of Hardy & Gawthorpe (1998) sediment is transported at a constant rate by a random walk algorithm from the source to the shore line. These models have no actual representation of channels in the topography. A more recent model by Sun *et alii*. (2002) is based on a cellular approach capable of representing channelized flow. Many of these models have operated on a rectangular grid (e.g. Coulthard *et alii*, 2000; Sun *et alii*, 2002), but model behaviour can be very sensitive to the grid orientation and spacing (Nicholas & Quine, 2007). Nicholas & Quine (2007) proposed a numeric fan evolution model with a radial grid focussed at the fan apex to represent the fan surface and a channel network represented by node positions. This model explicitly includes a process-form feedback at the channel scale in order to regulate the system response to erosion and deposition. However these models cannot be used to model debris flows because of a range of reasons: fluvial processes operate more continuously in time, changes to the surface morphology take place gradually and the sediment flux and maximum transportable grain size are typically limited by the flow velocity or the available stream power. In contrast, debris flows are events with a finite duration and a well-defined spatial extent. Debris flows self-channelize by thalweg erosion and deposition of levees (Blair & McPherson, 1998) but may be subject to abrupt avulsion, whereby relatively small sediment volumes deposited in critical places along the channel can force subsequent flows or flow surges in new directions (Blair & McPherson,, 1998; Whipple, 1992). In a single debris flow all available grain sizes are transported such that debris-flow deposits show limited or no down-fan fining (Blair & McPherson,, 1998; Kim & Lowe, 2004). Observations imply that erosion in debris flows may be largely a function of the inertial stresses induced by coarse particles carried in the flow front and impacting on the bed (Stock & Dietrich, 2006; Hsu *et alii*, 2008). None of the first class of models includes these effects explicitly.

The second class of models is designed to model sediment transport by single debris flows in a physically correct manner (e.g., Iverson, 1997; Iverson & Denlinger, 2001; Pudasaini, 2005; Patra *et alii*, 2005). They are based on grain-fluid mixture theory and yield depth-averaged equations for momentum and mass conservation, generally assuming constant flow mass. A major finding from simulations based on these models is that the total flow resistance depends more on boundary geometry than on boundary shear stress (Iverson & Denlinger, 2001). This is important for understanding how channel geometry affects flow behaviour. These models are not suitable for simulating fan development over long time scales because of their numerical complexity and long run times. Individual model runs can take from several minutes up to several hours depending on the size and resolution of the model space. This problem was discussed in detail by Dalbey *et alii* (2008) in the context of hazard assessment, where due to uncertainty in the input parameters hundreds of runs are necessary to explore the range of possible outcomes.

For some applications, the main interest lies in predicting only the inundation area of a flow of given volume over given terrain. This can be achieved at lower computational costs using empirical or semi-empirical relationships. For example, Griswold & Iverson (2007) and Berti & Simoni (2007) found a power-law relationship between total flow volume V [m^3] and inundated planimetric area B [m^2]:

$$B = \alpha\ V^{2/3} \qquad (1)$$

where α is a site-specific coefficient determined by regression. The smallest values of $\alpha = 6\text{-}7$ were reported by Crosta *et alii* (2003) for 138 granular debris flows with volumes of 2-10^5 m^3 (Central Italian Alps). A value of $\alpha = 20$ was reported by Griswold & Iverson (2007) from a worldwide data set of 44 non-volcanic debris flows ranging in volume from 10 to 10^7 m^3. Berti & Simoni (2007) suggested $\alpha = 33$ based on a data set of 24 granular debris flows with volumes of 500-$5 \cdot 10^5$ m^3 in the Italian Alps. While limited, these empirical relationships are appealing because of their simplicity.

EROSION AND DEPOSITION IN DEBRIS FLOWS

Debris flows can continue to erode material after initiation, but the same time material may be deposited at the flow margins. The net rate of this two-way exchange of material between the debris flow in motion and the channel bed is called the lag rate (CANNON, 1989). The lag rate is defined as the volume per unit downstream distance that is lost ($dV/dx < 0$) or gained ($dV/dx > 0$) by the flow. While this is clearly a key parameter for understanding how debris flows interact with their bed and banks and thus build topography, the controls on debris flow lag rate are not well known.

Debris flow erosion is particularly poorly understood (PUDASAINI, 2005; REMAITRE *et alii*, 2008) and difficult to predict. It is clear, however, that the erosion depth for transport limited conditions is highly variable in different settings (HUNGR *et alii*, 2005). Material can be incorporated into the flow by lateral erosion of the banks, bank collapse or entrainment of material from the channel bed. Experiments in small flumes with erodible beds of loose colluvium by EGASHIRA *et alii* (2001) and PAPA *et alii* (2004) have shown that erosion rates increase with increasing bed shear stress. BERGER *et alii* (2010) monitored the timing of erosion in a natural debris flow flowing on a bed of unconsolidated sediment, and found that it took place during passage of the flow front. STOCK & DIETRICH (2006) proposed a bedrock incision law for debris flows based on the inertial stress imparted to the bed by grain-bed impacts. The model predicts debris flows with long and coarse fronts and high shear rates (surface velocity / flow depth) to be most erosive. HSU *et alii* (2008) found a dependence of bedrock incision on grain diameter and to a smaller extent on shear rate of the flow, and suggested that most of the wear occurs underneath the coarse granular front. Despite these advances, a robust general model for debris flow erosion - akin to the geomorphic transport laws described by DIETRICH *et alii* (2003) - is still lacking.

The rates of deposition in a debris flow are closely linked to the runout length (CANNON, 1989; RICKENMANN, 2005, FANNIN & WISE, 2001). As a debris flow enters channel reaches with lower gradients, deposition becomes progressively more important, and eventually comes to dominate over erosion, leading to a net loss of flow volume (CANNON, 1989; RICKENMANN, 2005; HUNGR *et alii*, 2005; HÜRLIMANN *et alii*, 2003; FANNIN & WISE, 2001). The rate of deposition may increase dramatically on the lower parts of a fan where levee deposition is replaced by lobe formation (BLAIR & MCPHERSON, 1998). Despite these general observations, there remains no simple rule for the onset of deposition. FANNIN & WISE (2001) have shown that channel confinement plays a major role in triggering deposition. CANNON (1989) showed for one particular debris flow that channel geometry (triangular vs. rectangular section), channel width and strength or rheology of the flowing debris influence the rate of deposition. Other researchers have proposed that deposition starts at a particular bed slope angle, ranging from 3.5° to 40° (HUNGR, 2005). These data are derived from a great variety of debris flows, comprising ranges in for example volume, composition, channel geometry, and show that slope alone is not a good predictor for the onset of deposition. Work by IVERSON (1997) suggests that flow behaviour is best described by the granular temperature. The granular temperature is not a constant but rather a state variable that changes constantly as the flow moves, deposits and erodes material. Material with a high granular temperature is more likely to keep moving. When the granular temperature declines, the material will stop flowing eventually. All these observations are important for understanding the controls on debris flow deposition but they provide little guidance on how to predict the lag rate for a specific flow. We are only aware of one relationship that can be adapted to estimate the lag rate. GRISWOLD & IVERSON (2007) suggested an empirical relationship between total flow volume V [m^3] of a debris flow and the cross sectional area of the flow A [m^2]:

$$A = \varepsilon V^{2/3} \qquad (2)$$

where $\varepsilon = 0.1$ (regression based on 50 non-volcanic debris flows, worldwide). For granular debris flows in the Italian Alps (19 events) BERTI & SIMONI (2007) suggested $\varepsilon = 0.03$. This relationship can be interpreted as an upper limit on the rate of deposition, i.e. according to Eq. 2 a debris flow cannot deposit more than A m^3 of sediment per 1 m channel length. Where only levees are deposited the lag rate will necessarily be less because most of the flow cross section is made up by the channel. Note, too, that Eq. 2 does not allow for dependence on the channel geometry or gradient.

From field evidence it is known that debris flows can stop suddenly in a channel, forming a snout of coarse particles (e.g. WHIPPLE & DUNE, 1992; MCCOY *et alii*, 2010). This can cause the next flow to avulse into a new channel and lead to fundamental changes in the locus of sedimentation (WHIPPLE, 1992; BRYANT *et alii*, 1995; FIELD, 2001; DÜNFORTH *et alii*, 2008; REITZ *et* *alii*, 2010). Bryant *et alii* (1995) found an increase in avulsion frequency with increased sedimentation rates in a laboratory experiment of an alluvial fan. For understanding avulsion on debris-flow fans it is crucial to think about the conditions required to stop debris flows in a channel. Mccoy *et alii* (2010) suggested that the amount and persistence of excess pore pressures in the flow causes high mobility and long runout. Nevertheless the process of debris flow deposition is not understood well enough to make precise predictions of the location of the depositional snout along a predicted flow path.

DIRECT OBSERVATIONS OF DEBRIS FLOWS: IMPLICATIONS FOR MODELLING FAN EVOLUTION

The Illgraben in Switzerland is well known for frequent debris flows and is comprehensively monitored (McArdell *et alii*, 2007, Badoux *et alii*, 2008), providing an ideal opportunity to constrain relationships for flow erosion, deposition, and channel evolution on an active debris-flow fan. Since 2008 we have used a terrestrial laser scanner to map patterns and magnitudes of surface change due to single debris flows (Figure 1). Preliminary analysis of the data from individual flows shows that erosion and deposition can occur in the same event. Deposition in the form of levees along the flow margins (e.g., at Z and Y in Figure 1) and as sheets on inset terraces (W) occurs where flow depth is low. Along the centre line of the channel (e.g., at X) flow depth is substantially larger and incision is common. These observations have implications for the geomorphic impact of debris flows. Firstly, the effect of a single flow on a given channel depends not only on the flow magnitude (i.e. volume or peak discharge) but also on the channel geometry, and the effect can be very different across a given flow cross section. Secondly, flows of different magnitude occupying the same channel may behave differently because they "see" a different cross-section geometry, i.e. a different maximum flow depth and different inundation limits. We suspect that this mechanism gives rise to a poorly understood set of process-form feedbacks which influence how debris-flow fan systems evolve over time.

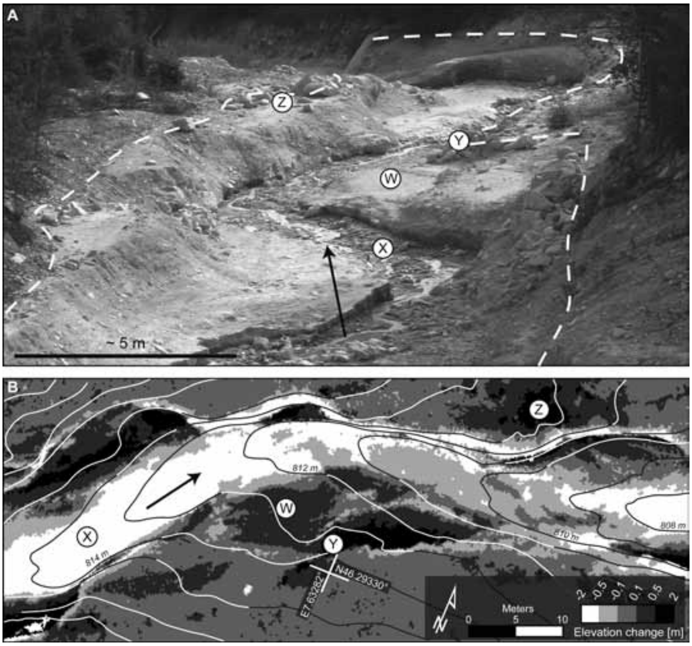

Fig. 1 - Channel geometry and elevation change due to a debris flow on 1 July 2008 of 60000 m³ total volume and peak discharge ~100 m³/s, both measured at the toe of the fan at Illgraben, Switzerland. Black arrows indicate flow direction. Corresponding locations in the photo and on the map are indicated by W, X, Y and Z. Elevations represent post-flow topography and are given in meters above sea level, spacing of contours is 1 m. A: Portion of the monitored reach near the fan apex (looking downstream). White dashed line indicates the maximum extent of inundation by the flow. Note levee deposits on flow margins near Y and Z, sheet-like deposits near W on inset terrace and incision near X. B: Difference model obtained by repeat terrestrial laser scanning of the study reach. Grey scale values indicate surface elevation change during the event

A NEW MODEL: CONCEPTUAL FRAMEWORK

The new debris-flow fan evolution model we propose in this paper overcomes some of the shortcomings of existing fan evolution models by better representing the behaviour of debris flows. In the design of the model we place particular emphasis on the aforementioned process-form feedbacks which are most relevant for landform generation. From observations of erosion and deposition in debris flows we can formulate a number of requirements for the new model:

(1) Flows should self-channelize when moving across unconfined fan surfaces.
(2) Debris flows should erode the fan surface when certain criteria are met.
(3) Periodic avulsion and shifting of the depocenter should be permitted when certain conditions are met.
(4) The emergent channel scaling should be comparable to the scaling on natural fans.
(5) Flows should stop at a range of distances from the fan head.

The model must be computationally efficient in order to simulate the cumulative influence of a large numbers of successive flows over geological time scales. This can be achieved via a set of flow rules, which must cover the routing of flows down the fan surface, the rates and location of both erosion and deposition, and criteria to stop flows on the fan.

MODEL STRUCTURE

The model reads the initial topography from a DEM. Subsequently a flow routing algorithm identifies the most likely flow path between the flow initiation or entry point and the model boundaries. Then we extract channel cross sections at defined intervals. At each cross section we test whether the channel conveyance capacity is exceeded or not and we estimate the flow depth in each cross section. We then use this information to inform the flow behaviour (erosion, deposition, stop) and calculate the lag rate. Next, we update both the DEM and the flow characteristics dependant on the model rules. With these updated values we move to the next cross section. When the flow stops a new flow will be released onto the modified DEM. This approach requires a series of approximations, which we will discuss below.

Starting at the topmost cross section we estimate flow cross-sectional area as a function of total flow volume using Eq. 2. Then we test whether the channel at the location of the active cross section can contain the flow or not (Figure 2). If it does, we determine the degree of in-channel erosion or deposition by applying the rules outlined below. If the flow is not contained within the channel, we estimate the required width to contain the excess discharge. In this way we identify the inundated area on both sides of the channel and assume deposition in those areas. We apply the resultant amount of erosion or deposition to the DEM area between the active and the next cross section. After updating the volume of the debris flow we test the stop criterion. As long as this is not met we proceed to the next cross section.

INITIAL AND BOUNDARY CONDITIONS

We run the model on an irregular triangular mesh. Debris flows are released into the model domain at the fan apex with an initial volume and an initial sediment concentration. For each flow we randomly choose these values from a probability distribution function (PDF).

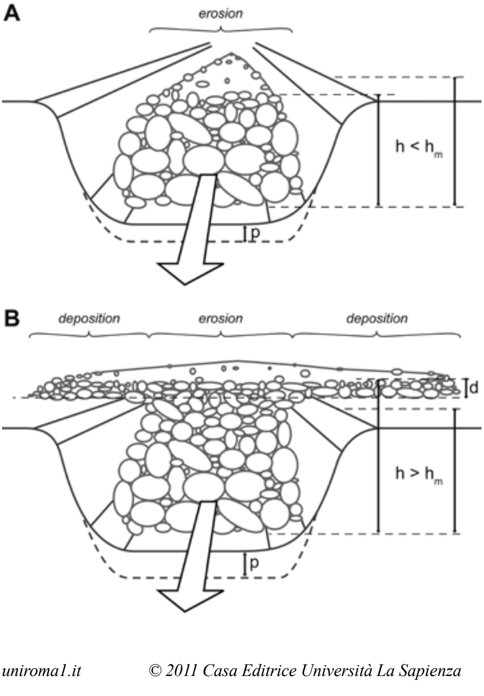

Fig. 2 - Application of erosion and deposition rule. Flow direction indicated by arrow. Symbols: h, flow depth;hm, maximum flow depth at channel conveyance capacity; d, thickness of deposits; p, entrainment depth. A: Debris flow with peak discharge smaller than channel conveyance capacity. B: Debris flow with peak discharge exceeding channel capacity

For debris flow magnitude we use published data (Helsen *et alii*, 2002; Hungr *et alii*, 2008; Jakob & Friele, 2010), and data from 10 years of debris flow monitoring at Illgraben, Switzerland; synthetic distributions such as log-normal or double Pareto may be defined. The initial sediment concentration is based upon observations at Illgraben that span a range of volume fractions of 0.15-0.75 (data from 35 events).

DEPOSITION RULE

Debris flow deposits can be grouped into two types: levees and lobes (Blair & Mcpherson, 1998; Kim & Lowe, 2004). Levees are deposited while the major part of the debris flow is still in motion and are, given sufficient accommodation, left behind on one or both sides of the flow path. They are often triangular or box-shaped in cross profile (Blair & Mcpherson, 1998; Kim & Lowe, 2004), where the height is similar to the size of the largest particles in the flow (McCoy *et alii*, 2010) and rarely higher than ~2-3 m (Blair & Mcpherson, 1998; Kim & Lowe, 2004). The geometry of depositional lobes is more difficult to generalize, although their thickness may be similar to the height of levees (Blair & Mcpherson, 1998). The spatial extent of lobes depends on a variety of factors such as accommodation, available flow volume to be deposited (Blair & Mcpherson, 1998) and possibly surface slope.

With these observations in mind, Eq. 1 can be rewritten in terms of average deposit thickness d (Berti & Simoni, 2007)

$$d = 1/\alpha\ V^{1/3} \qquad (3)$$

which is supported by the observation that debris flow lobe deposits have a roughly constant thickness for any given event (Iverson *et alii*, 1998; Legros, 2002). With $1/\alpha = 0.06$ (Berti & Simoni, 2007) Eq. 3 predicts a deposit thickness of 0.6 m for a flow of $V = 1000\ m^3$, or 2.7 m for $V = 10^5\ m^3$. These estimates are roughly compatible with our own observations for flows and associated deposits at Illgraben, Switzerland.

We use the fact that deposition in a cross section occurs where flow depth is low compared to the deeper parts of the channel (Figure 1), and that Eq. 3 can inform a minimum flow depth below which deposition occurs, to define our deposition rule. Figure 2B illustrates this: a flow with a peak discharge exceeding the channel conveyance capacity will have very different flow depths along the centreline of the channel and in the overbank area. The excess discharge not contained in the channel will spread over-bank until it reaches a minimum flow depth of *d* and we assume that it will stop flowing when it has reached this degree of spreading. In a situation as shown in Figure 2A, where the channel conveyance capacity is not exceeded, we can apply the same concept and test whether the maximum flow cross-sectional area (as determined by Eq. 2) leads to a flow depth of more than the required minimum flow depth defined by Eq. 3 in the given cross section.

EROSION RULE

For simplicity, we focus here upon entrainment from the channel bed because bank collapse and lateral erosion are not well represented at the fan scale. We link the erosion rule to basal shear stress τ, defined as:

$$\tau = \rho\, g\, h\, S \qquad (4)$$

where ρ is density, g is gravitational acceleration, h is flow depth and S is channel slope. This assumes that the stresses imposed on the channel bed are larger for greater flow depths, irrespective of the main driver of erosion (e.g., bed shear stress or inertial stresses due to grain impacts), and that erosion is most likely where basal shear stress is largest (Papa *et alii*, 2004). The erosion rule is invoked when the flow depth exceeds the threshold for deposition d (Eq. 3). We use data on maximum flow depth versus erosion depth from monitoring (Figure 1) to define probability distribution functions (PDF) of erosion at a given level of basal shear stress. The erosion depth is then determined by random sampling from this PDF.

STOP RULE

We make two simple assumptions about the conditions that define when debris flows stop. A flow obviously needs to stop when all or almost all material is deposited. Further, we assume that debris flows can only entrain material to a certain maximum volume fraction of sediment (e.g. 0.8) before internal friction prevents further motion. Critical to this is a consideration of channel bed saturation. The channel bed may be dry or saturated before the event according to a probability specified by the user. If the bed is saturated (e.g. vol. fraction of 10%), then erosion not only adds sediment to the flow but also water, and hence the flow mobility is expected to increase. In the case of a dry channel bed, the maximum volumetric sediment concentration is reached faster and the flows are therefore less mobile. The sediment-concentration criterion is designed to reproduce the stochastic nature of avulsion events and to force the model to abandon established channels and establish new depositional lobes and channels.

MODEL VALIDATION

As this model will be useful for both landscape evolution analysis and short-term hazard analysis we need to validate it for both types of applications. The short-term performance of the model is validated using a series of well documented debris flows at the Illgraben. This requires high-resolution topographic data (e.g. airborne LiDAR) of the fan surface, event data on flow magnitude and discharge, and the geometry of associated deposits. The long-term performance of the model is compared against two well-documented debris flow fans. The first test case is the Illgraben fan in Switzerland where we have a good understanding of the historical magnitude-frequency distribution of debris flows and of their properties. In addition we have established a depositional chronology for this fan from the analysis of airborne LiDAR and field mapping. The second test case is the Shepherd Creek fan in Owens Valley, California, for which similar data on topography and fan chronology are available. Dühnforth *et alii* (2007) have applied cosmogenic dating to constrain ages of depositional lobes on the Shepherd Creek fan which can be used to constrain sedimentation rates and avulsion frequencies produced by the model.

PRELIMINARY RESULTS

In Figure 3 we show preliminary results of a pilot version of the proposed model. In the pilot version we model the evolution of a single channel cross section at a distance *R* of 250 m from the fan toe over a sequence of 500 debris flows (Figure 3C). Debris flow volumes are sampled from a lognormal distribution with a mean of 27’000 m^3 and a standard deviation of 13’000 m^3. The probability of avulsion is set to 0.08, with $\varepsilon = 0.1$ and $\alpha = 20$ (Eq. 2 and 3). Changes in channel thalweg elevation (E) due to erosion or deposition affect the channel slope: $S = E / R$. Thalweg elevation and channel slope fluctuate as a function of erosion and deposition (Figure 3A). Periods of gradual incision (time steps 150-200) occur as well as phases of aggradation corresponding to avulsion events (e.g. time step 302). Figure 3B shows the relative lag rate per event; this is the erosion or deposition volume divided by initial volume *V*. The negative spikes with values of -100% represent avulsion events.

MODEL OUTPUT AND DISCUSSION

With this model we can investigate a set of questions related to the deposition and erosion dynamics of debris-flow fans. A first application concerns debris-flow magnitude-frequency distributions. These distributions for particular fans are usually poorly constrained due to incomplete historical records (Jakob & Friele, 2010). With our model we can test whether different

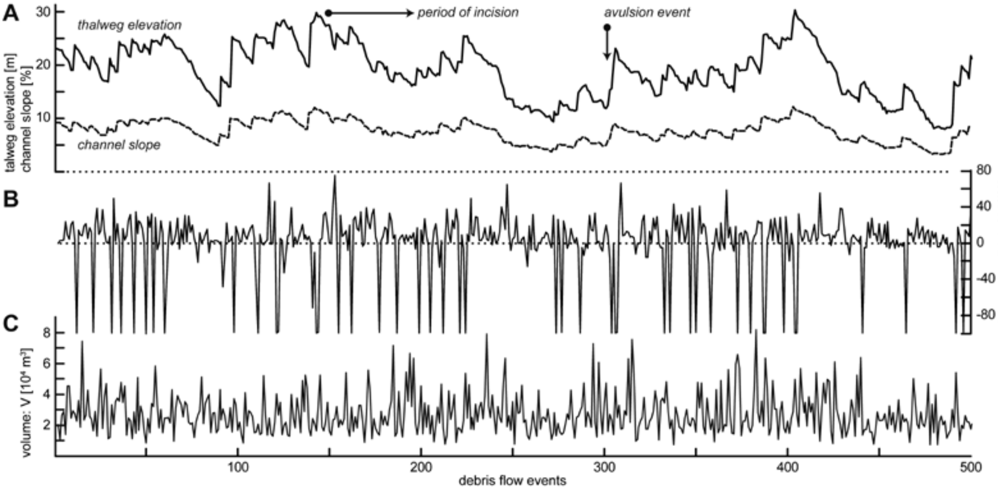

Fig. 3 - Preliminary model results showing the evolution of a single channel cross section over a sequence of 500 debris flows. A: Evolution of thalweg elevation and channel slope. B: Relative lag rate dV/dx, normalized by initial flow volume V. Note: positive values mean entrainment and negative values mean deposition. C: Event volumes sampled from a lognormal probability distribution with a mean of 27’000 m^3 and a standard deviation of 13’000 m^3

input magnitude-frequency distributions of debris flow volumes have a significant effect on fan morphology or evolution. In particular we can look at variables such as channel scaling, the distribution of runout distance preserved in the deposits, or the frequency of avulsion events. If these vary for different model input volume distributions, they could be used to infer the input magnitude-frequency distribution of debris flow volumes from geomorphic mapping of fan surfaces.

Secondly, we can investigate the causes of fan head incision. The mechanisms of fan head incision on alluvial and debris flow fans are widely discussed (Harvey, 1984; Harvey, 2005; Davies & Korup, 2007; Dühnforth *et alii*, 2008). A range of external and internal forcing mechanisms has been proposed (see full discussion in Dühnforth *et alii*, 2008). With our model we can investigate whether a process-form feedback is sufficient to create incised channels and judge how stable such a configuration might be. In other words, we ask whether the random selection of events (picked from a PDF of flow volumes) is sufficient for the development of an incised state. Our preliminary results (Figure 3) suggest that this is the case.

Thirdly, we can use the model to investigate channel avulsion and the switching between different depositional lobes. Channel avulsion is a major concern on many fans where lives or infrastructure are at risk. With this model we can test an existing channel configuration obtained from real fan topography with a finite number of randomly chosen possible flows. This experiment highlights: 1) where in the channel network avulsion is most likely to occur, and 2) what conditions are most likely to lead to avulsion.

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