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1 Dynamic controls on erosion and deposition on debris-flow fans

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8 **ABSTRACT**

9 Debris flows are amongst the most hazardous and unpredictable of surface processes in
10 mountainous areas. This is partly because debris-flow erosion and deposition are poorly
11 understood, resulting in major uncertainties in flow behavior, channel stability and sequential
12 effects of multiple flows. Here we apply terrestrial laser scanning and flow hydrograph analysis
13 to quantify erosion and deposition in a series of debris flows at Illgraben, Switzerland. We
14 identify flow depth as an important control on the pattern and magnitude of erosion, whereas
15 deposition is governed more by the geometry of flow margins. The relationship between flow
16 depth and erosion is visible both at the reach scale and at the scale of the entire fan. Maximum
17 flow depth is a function of debris flow front discharge and pre-flow channel cross section
18 geometry, and this dual control gives rise to complex interactions with implications for long-term
19 channel stability, the use of fan stratigraphy for reconstruction of past debris flow regimes, and
20 the predictability of debris flow hazards.

21 **INTRODUCTION**

22 Debris flows are a ubiquitous hazard in mountain areas, not least because of their ability
23 to avulse from an existing channel and inundate adjacent areas on debris-flow fans (Rickenmann

24 and Chen, 2003; Jakob and Hungr, 2005). The avulsion probability is controlled mainly by the
25 ratio of flow peak discharge and channel conveyance capacity. While the latter can be estimated
26 from field measurements (Whipple and Dunne, 1992), both parameters can change rapidly
27 during a flow due to erosion and deposition along the flow path (Fannin and Wise, 2001). This
28 not only makes it difficult to predict the temporal evolution of an individual flow, but also
29 changes the boundary conditions for the next flow in that channel. There results a critical need to
30 understand the dynamic relationships and feedbacks between debris flow volume and the
31 changes in channel topography due to erosion and deposition as the flows traverse a fan.

32 Previous studies have focused more on debris-flow deposition than on the mechanics of
33 erosion, and published work on erosion is partly contradictory. Takahashi (2007) found that the
34 concentration of coarse particles in a debris flow increases with bed slope, and that erosion is
35 only possible when the flow is undersaturated in coarse particles. But field observations,
36 however, indicate that erosion occurs mostly during passage of the granular flow front (Berger et
37 al., 2011), and is likely associated with impacts of coarse sediment on the bed. Iverson et al.
38 (2011) explored the role of bed properties and found a positive correlation between erosional
39 scour depth and bed water content. Debris-flow deposition has been related to channel gradient
40 (Cannon, 1989; Fannin and Wise, 2001; Hungr et al., 2005; Hürlimann et al., 2003), downstream
41 channel widening (Cannon, 1989; Fannin and Wise, 2001), or flow volume, based on an
42 observed power-law relationship between flow volume and total inundated area (Griswold and
43 Iverson, 2007). More generally, detailed monitoring of experimental flows (Major and Iverson,
44 1999) and physically-based description of fluid-solid mixtures (Iverson, 1997) have related flow
45 mobility to granular temperature, defined as the mean square of particle velocity fluctuations,

46 and excess pore-fluid pressure (McCoy et al., 2010). These effects are counteracted by friction at
47 the dry coarse-grained flow margins (Major and Iverson, 1999).

48 The objective of this study is to understand the interaction between a debris flow and the
49 channel bed by systematically measuring erosion and deposition in a series of natural flows at
50 both the reach and fan scales. We hypothesize, based on the results of Berger et al. (2011), that
51 local bed elevation change is related to basal shear stress (and thus to maximum flow depth) and
52 flow volume. We use a terrestrial laser scanner (TLS) to determine high-resolution reach-scale
53 measurements of erosion and deposition in a natural channel caused by four debris flows. We
54 then relate these data both to flow depth and to fan-scale flow volume changes estimated from
55 debris-flow hydrographs.

56

57 **STUDY AREA**

58 The Illgraben debris flow fan is situated in the Rhone valley, Switzerland (Fig. 1) and has
59 a long history of debris flows (Marchand, 1871; Lichtenhahn, 1971). The fan has an area of 6.6
60 km² with a radius of 2 km and a gradient that decreases from 10% to 8% down-fan (Schlunegger
61 et al., 2009). The bedrock geology in the catchment is dominated by schist, dolomite breccia and
62 quartzite (Gabus et al., 2008). The lowermost bedrock along the Illgraben channel outcrops just
63 below a sediment retention dam (check dam 1, Fig. 1); downstream the channel bed consists of
64 unconsolidated sediments. Convective storms from May to September trigger three to five debris
65 flows per year (McArdell et al., 2007). In the 1970s a series of concrete check dams (CD) were
66 constructed to limit erosion and control the channel position on the fan (Lichtenhahn, 1971).
67 Flow hydrograph and onset data are available from two gauging stations at CD10 near the fan
68 apex (Fig. 1, Badoux et al., 2009) and CD29 at the fan toe (McArdell et al., 2007). Since 2007

69 we have monitored the channel bed using TLS in an unconfined 300 m study reach between
70 CD16 and 19 (Fig. 1).

71

72 **METHODS**

73 We surveyed the study reach before and after debris flows using a Trimble GS200
74 terrestrial laser scanner yielding point clouds of $\sim 10^7$ vertices per survey. Data from individual
75 scan positions and subsequent surveys were merged into one coordinate system using an iterative
76 closest point matching algorithm (Besl and McKay, 1992). We gridded the data to a 0.2 m
77 resolution DEM and calculated difference models (Fig. 2) from subsequent surveys; this yields a
78 conservative estimate for erosion because it includes deposition in the falling limb of the flow
79 hydrograph (Berger et al., 2011). For each flow, we mapped maximum inundation limits from
80 levees and mudlines along the channel, and interpolated these to a 0.2 m resolution maximum
81 flow stage surface. Our estimated uncertainty on this surface is ± 0.25 m, given the difficulties in
82 identifying the mudline in the field due to splashing and poor preservation. The maximum flow
83 stage surface is a lower estimate as the flow surface is generally convex up in cross section. Flow
84 depth was taken as the difference between the maximum flow stage surface and the pre-event
85 DEM. We analyzed the relationship between flow depth and channel change via a cell-by-cell
86 comparison of flow depth with the difference model (Fig. 3A).

87 To understand how fan-scale flow volume change relates to flow properties, we estimated
88 volumes and debris flow front heights from the first surge for 14 debris flows in 2007–2009
89 (Table DR1) from flow hydrographs measured at the CD10 and CD29 gauging stations. From
90 measurement of the front velocity of each flow, we calibrated a Manning-type friction relation
91 (Schlunegger et al., 2009) to estimate mean flow velocity as a function of flow stage (see Data

92 Repository). The friction relation is then used to integrate the hydrograph over the event duration
93 to obtain the total flow volumes at both the apex (CD10) and toe (CD29) of the fan.

94

95 **RESULTS**

96 The difference DEMs for events 11 and 14 (Fig. 2) show that both events caused net
97 erosion within the study reach, leading to increases in flow volume of $87 \pm 6 \text{ m}^3$ and 2039 ± 4
98 m^3 , respectively, but that the spatial patterns of erosion and deposition are very different. Event
99 11 shows alternating regions of erosion and deposition, with erosion along the deepest parts of
100 the channel and on the outside of bends, and discontinuous levee deposits along the flow margins
101 and on shallow terraces (Fig. 2A). The maximum discharge in this event was $\sim 60 \text{ m}^3 \text{ s}^{-1}$
102 calculated at CD10. In event 14, the deepest parts of the channel were eroded continuously
103 throughout the reach; zones of deposition correspond to localized over-bank spill and several
104 large boulders ($D > 2 \text{ m}$) have been emplaced along the flow margins (Fig. 2B). The average
105 flow depth in the channel was substantially larger than in event 11 and we estimate a maximum
106 discharge of $\sim 630 \text{ m}^3 \text{ s}^{-1}$ at CD10.

107 By combining estimated maximum flow depth in each grid cell with the measured
108 elevation change in that cell for events 9, 11, 12 and 14, we can evaluate the effect of flow depth
109 on the probability of erosion or deposition (Fig. 3A). The data illustrate two important
110 observations: that substantial erosion is more likely with increased flow depth, but also that a
111 broad range of outcomes is possible at any given flow depth.

112 Flow depth also appears to control debris-flow behavior at the fan scale. Of the 14 events
113 in Figure 3B, 11 led to net deposition on the fan and three (5, 9, 13) to net erosion when
114 comparing flow volumes at CD10 and CD29. All erosive events had front heights greater than

115 2.3 m, and all depositional events (except 14) had front heights less than 2.7 m. Event 14
116 consisted of two surges within the first 17 s with front heights of 2.3 m and 5.2 m respectively.
117 By CD29, only a single surge was discernable, with a front height of 2.5 m. At the fan scale this
118 event was clearly depositional (Fig. 3A). However, visual inspection of the channel showed that
119 it was highly erosive on the upper part of the fan (between CD10 and 16), including the study
120 reach (Fig. 2B), while downstream of CD18 we observed widespread deposition on inset
121 terraces.

122

123 **DISCUSSION AND CONCLUSIONS**

124 We have established a unique record showing correlation between flow depth and erosion
125 or deposition in debris flows (Fig. 3A). At flow depths of less than 1.5 m the probability
126 distribution function (PDF) of bed elevation change approaches symmetry around zero: erosion
127 and deposition are equally likely. As flow depth increases, the PDF widens to include the
128 possibility of high erosion values, while the probability of deposition decreases moderately. At a
129 flow depth of 1–2 m the probability of deposition is up to 50%, while at a depth of 3 m the
130 probability of deposition is less than 25%. Flow depth exerts a much stronger influence in the
131 erosional domain: the 10%, 25% and 50% quantiles of erosion all show an increase at flow
132 depths greater than ~2 m. Furthermore, between 2 and 3 m flow depth, the likely amount of
133 erosion at any given probability level approximately doubles.

134 Flow depth is largest at the debris flow front (Iverson, 1997; McArdell et al., 2007) and
135 the majority of erosion takes place during its passage (Berger et al., 2011). The flow depth at the
136 front influences the forces acting on the channel bed via three mechanisms: higher basal shear
137 stress, the impact stresses of coarse particles recirculating in the flow front (Suwa, 1988; Stock

138 and Dietrich, 2006; Hsu et al., 2008), and hydraulic pressure at the flow front that may cause
139 rapid undrained loading (Hung et al., 2005) and liquefaction of the channel bed (Sassa and
140 Wang, 2005). Although all three processes may be relevant here, we lack data on the second and
141 third mechanisms. We can evaluate the first by converting flow depth to basal shear stress (Fig.
142 3A), defined as $\tau = \rho g h S$ where ρ is density, g is gravity, h is flow depth and S is channel
143 slope. Taking an observed median density of debris flow fronts at Illgraben of 1800 kg/m^3 (35
144 events) and slopes of 8%–10%, we find that substantial erosion takes place when a basal shear
145 stress of 3–4 kPa is exceeded, which is consistent with erosion monitoring near CD29 (Berger et
146 al., 2011). Whether this shear stress reflects an effective strength of bed material, or is instead
147 analogous to a threshold shear stress for fluvial entrainment, is not clear from our data. Other
148 effects such as grain impact (Berger et al., 2011) or antecedent moisture conditions of the bed
149 (Iverson et al., 2011) are relevant as well.

150 In contrast, debris-flow deposition occurs dominantly along the flow margins and where
151 the flows spread over low-relief areas adjacent to the channel (Fig. 2). As has been argued
152 elsewhere (e.g., Cannon, 1989; Major and Iverson, 1999; Fannin and Wise, 2001) that this
153 pattern is consistent with the triggering of deposition by increased friction along the flow
154 margins, and by changes in local channel geometry. This is illustrated in Figure 2 by substantial
155 deposition in the lower, wider cross-sections rather than the narrow upstream section of the
156 reach.

157 If debris-flow front height is a key variable in determining flow behavior, then what are
158 its primary controls? Front height is proportional to discharge but is dynamically adjusted as the
159 channel cross-section geometry changes along the flow path. Sudden changes in channel
160 geometry can reduce the maximum flow depth and cause both over-bank deposition and,

161 critically, a decrease in basal shear stress within the channel, potentially leading to the onset of
162 in-channel deposition (Cannon, 1989). Front height is also likely to vary with the proportion of
163 the coarse sediment fraction. Coarse debris flow fronts have very low fluid pressures (Iverson,
164 1997; McArdell et al., 2007), leading to the analogy of these steep and dry flow fronts as mobile
165 dams (Major and Iverson, 1999). As a thought experiment, consider such a mobile dam with a
166 triangular cross-section in a channel ~4 m deep and 10 m wide, implying a total of ~160 m³ of
167 material to build. Because coarse particles are recirculated in the flow front (Suwa, 1988;
168 Iverson, 1997) a debris flow probably requires a multiple of this volume to sustain the mobile
169 dam, but even this is a small amount of material compared to typical Illgraben flow volumes
170 (Table DR1). Thus, the loss of even moderate volumes of coarse debris to levee deposition may
171 lead to a fundamental downstream change in behavior as flow height decreases. Event 14, which
172 showed a rapid downstream transition from dominantly erosional to dominantly depositional
173 behavior, may represent an example of this process.

174 Our findings also have implications for the channel evolution over the course of
175 sequential events. Figure 4 shows per-event and cumulative fan-scale changes in flow volume,
176 indicating three phases of aggradation each followed by an erosive event. The state of the
177 channel changes as a result of these events: in events with a very high front we expect deposition
178 on the channel banks and erosion along the center-line (e.g., Fig. 2B); a medium front height in
179 the same channel might only erode along the center line; and events with even smaller flow
180 fronts might gradually fill the channel by deposition of lobes and inset levees. As a result, similar
181 consecutive events entering the apex of the fan will experience a different channel cross-section
182 than their predecessors and will undergo different downfan changes in volume increase or loss.
183 The cycles of filling and evacuating the channel observed here are evocative of larger-scale

184 autocyclic storage and release of sediment on alluvial fans (Kim et al., 2006; Kim and Muto,
185 2007) and have major implications for the preservation of debris-flow fan stratigraphy, even in
186 the absence of temporal variations in external controls such as climate, tectonics or changes in
187 sediment supply. In addition, the lack of correlation ($R^2 = 0.0004$) between flow volume and
188 front height (Fig. 3B) means that (perhaps counter-intuitively) flows with larger total volumes
189 may not necessarily pose the greatest hazard of avulsion. The dependence of flow volume
190 change on the local channel characteristics and the history of previous flows are likely to
191 complicate efforts to define hazard by establishing magnitude-frequency distributions for
192 particular catchments (Zimmermann et al., 1997; Hungr et al., 2008; Jakob and Friele, 2010;
193 Stoffel, 2010) without a better understanding of downstream flow evolution.

194

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200

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286 **FIGURE CAPTIONS**

287 Figure 1. Overview of the Illgraben catchment and fan in southeastern Switzerland. Tributary
288 joining downstream of check dam (CD10) is inactive due to hydro-power dam in headwaters.
289 Geophones are mounted on CDs 1, 9, 10, 28 and 29. Flow stage measurements are taken at
290 CD10 (radar) and 29 (laser and radar). Study reach is located between CD16 and 19. Contour
291 interval is 50 m on the fan and 400 m for altitudes above 800 m a.s.l.

292 Figure 2. Difference DEMs (0.2 m cell size) for (A) flow 11 and (B) flow 14. See Table DR1 for
293 flow details. The background hillshade image represents pre-event topography. Color scale
294 values indicate surface elevation change during the flow; elevation change less than ± 0.1 m is
295 shown in white due to uncertainty caused by small-scale surface roughness. Center panels show
296 elevation change in selected cross sections; black line indicates pre-event topography, red line
297 indicates post-event topography, and blue line indicates maximum flow stage in the channel.
298 Contour interval is 5 m. Red circle (panel B): boulders deposited over-bank.

299 Figure 3. A: Percentile plot of cell by cell comparison of elevation change (erosion or deposition)
300 against maximum flow depth for events 9, 11, 12 and 14. The top axis shows estimated basal
301 shear stress for channel slopes of 8% (above) and 10% (below). Grey shades show contours of
302 raw data density based on a bin size of 0.5 m in flow depth (shown by the solid box). The
303 ensemble of percentile lines illustrates the frequency distribution of elevation change at any
304 given flow depth. Total number of data points is 565,344. See Fig. DR3 for individual events.
305 B: Fan-scale flow volume change against flow front depth at CD10 for 14 events between 2007
306 and 2009. Numbers next to symbols indicate event number. See Table DR1 for flow details. Box
307 width indicates event volume at CD10. Volumes include both water and sediment. Arrow
308 indicates height of second surge in event 14.

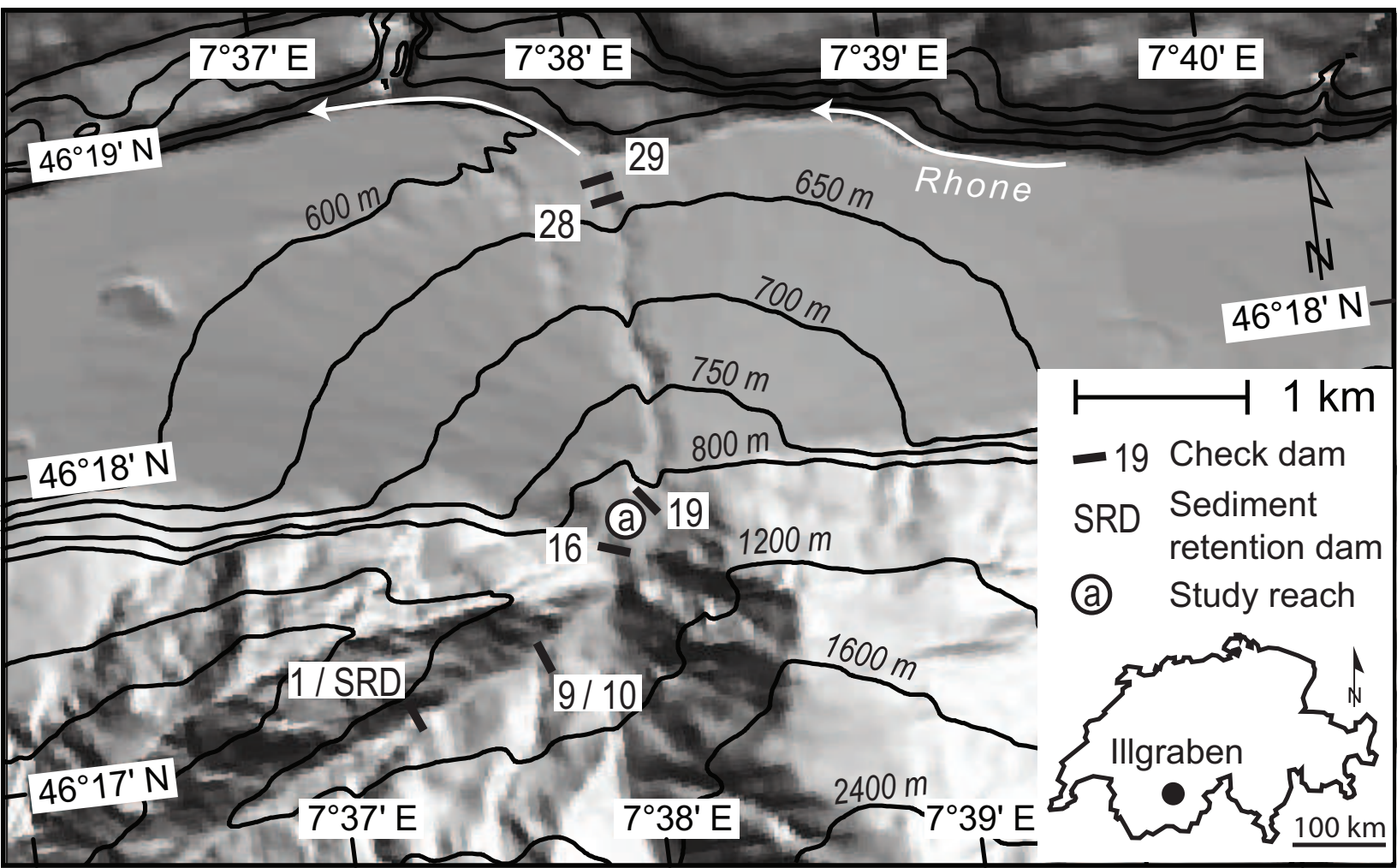
309 Figure 4. Time series of erosional (negative) or depositional (positive) volume change per event,
310 calculated as the difference between volumes at CD10 and 29 (gray bars) with event numbers
311 (Table DR1) and cumulative volume change (black line).

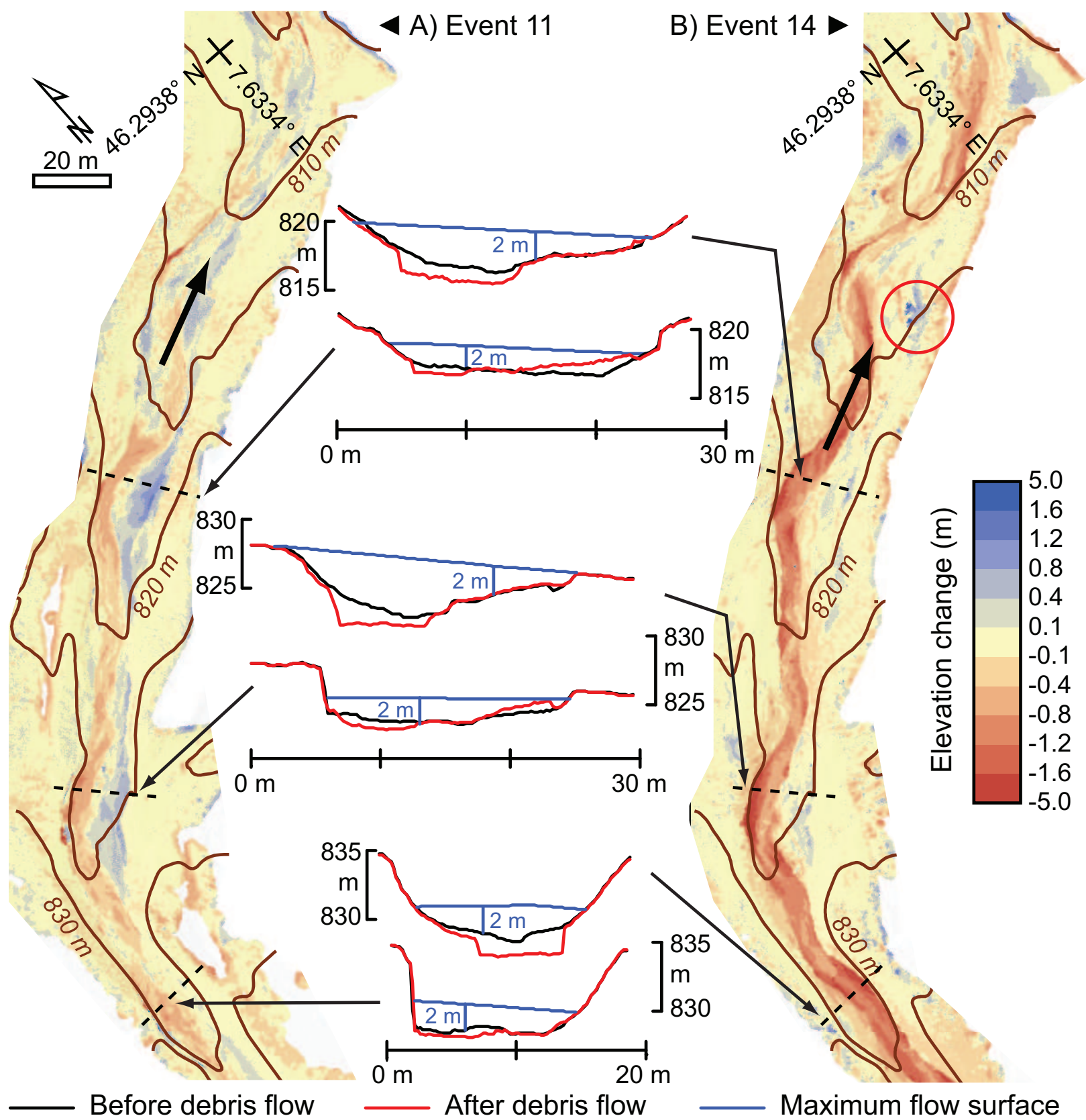
312 ¹GSA Data Repository item 2011xxx, table with data for debris flows discussed in the text and
313 additional percentile and density plots for individual events, is available online at

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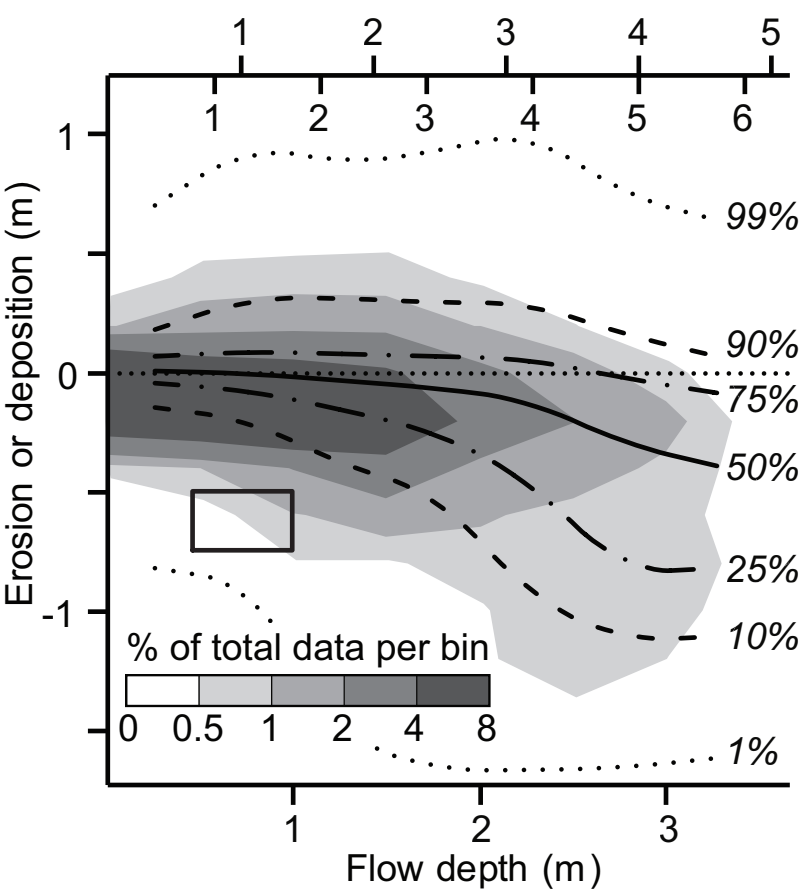
314 www.geosociety.org/pubs/ft2009.htm, or on request from editing@geosociety.org or Documents

315 Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.





A τ at slope of 8% (10% bottom scale) (kPa)



B

Volume estimated at CD 10:

■ 10^4 m^3 ■ $2.5 \cdot 10^4 \text{ m}^3$ ■ $5 \cdot 10^4 \text{ m}^3$

