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Sediment Transport and Bedrock Erosion by Wet Snow Avalanches in the Guggigraben, Matter Valley, Switzerland

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Abstract

Wet snow avalanches breaking through to the base of the snowpack or overriding snow-free surfaces can entrain basal material and act as important agents of sediment transport in steep alpine catchments. Here we present results from 4 years of measurements at the Guggigraben catchment (Matter Valley, Canton Valais), quantifying the volume of sediment transported by avalanches each winter season. Sediment load was estimated by measuring the debris content within representative areas and then extrapolating the cumulative volume. Results reveal a total transported sediment volume of 70 m³ in 2009, 23 m³ in 2010, 15 m³ in 2011, and 35 m³ in 2012, which correspond to catchment-wide erosion rates of approximately 0.05, 0.02, 0.01, and 0.03 mm/a, respectively. Sediment appears to be sourced predominantly from within the main channel or one its tributaries, originating first from rockfall or landslides. Avalanches thus play an important role at the Guggigraben in transporting loose sediment from temporary storage sites to the fan and main river system. Within the bedrock gully and in the avalanche source region above, signs of abrasive wear were evident on exposed bedrock surfaces. These included rounded and scoured bedrock, fresh boulder impacts, and scratch marks on the gully walls.

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Introduction

The ability of snow avalanches to erode their substrate and entrain rock debris during runout can make them effective agents of mass transport in steep alpine catchments (Gardner, 1970; Luckman, 1977). Moreover, their regular occurrence in certain topographic and climatic settings means that specific, identifiable areas of the alpine landscape are regularly affected by snow avalanche erosion from year to year (Rapp, 1960). While the geomorphic significance of avalanche erosion has been recognized for some time (e.g. Allix, 1924; Matthes, 1938), relatively few quantitative studies exist at present that examine their effects in sculpting bedrock landforms and transporting sediment from the upper reaches of a catchment to adjacent fans and river systems. Large unknowns thus remain relating to the mechanics and efficacy of avalanche erosion, and its relative role in mass transport from alpine catchments.

Wet snow avalanches refer to predominantly springtime avalanche events where the snowpack attains a relatively high water content creating dense and compact mass flows (Keylock, 1997; McClung and Schaerer, 1993). Such events are common in late spring during periods of rapid snowmelt or rainfall, and their deposits commonly consist of packed “snow balls,” decimeter-sized agglomerations of snow and ice (Jomelli and Bertran, 2001). This type of avalanche stands in contrast to *dry snow* avalanches, which are predominantly wintertime phenomena with characteristically lower water content and density (McClung and Schaerer, 1993). *Dirty avalanches* (Rapp, 1960) refer to any type of snow avalanche that has entrained soil, rock, and organic material in varying quantities during its initial motion or runout. Boulders with dimensions

up to meters can be entrained and transported (Rapp, 1959). The deposits thus appear characteristically brown and dirty, in contrast to clean white snow avalanches that prevail throughout much of the winter. Dirty avalanches are by definition the event type of interest in analysis of avalanche erosion and sediment transport.

Wet snow avalanches in spring have several characteristics that make them more effective erosional agents than their wintertime counterparts (Gardner, 1983): (a) their higher density means they are more easily able to pluck, entrain, and transport coarse sediment; (b) isothermal snowpack conditions means these avalanches commonly break through the full depth of the snowpack, sliding directly over the hillslope surface; and (c) down-slope areas are more likely to be snow free, meaning the avalanche has a higher probability of traversing erodible hillslope substrate. Once they have entrained rock debris, irregular impacts and abrasion between transported boulders and bedrock surfaces occur as the avalanches run over snow-free areas, and especially when channelized in steep gullies. This abrasive wear (or corrosion) can play an important role in eroding material and sculpting bedrock gullies—avalanches erode rock surfaces several meters above active stream channels, strip loose material from ledges and intermediate storage sites (Rapp, 1960), and can create characteristically smooth and rounded gullies on high mountain flanks where regular stream flows are rare (Allix, 1924; Matthes, 1938).

Transport of rock debris by wet snow avalanches has been quantitatively documented in a number of previous studies, including Allix (1924), Rapp (1960), Gardner (1970, 1983), Luckman (1977, 1978); Ackroyd (1986), Bell et al. (1990), Heckmann et al. (2005), Sass et al. (2010), and Freppaz et al. (2010). These observational investigations laid the important foundation for eval-

uating the erosional efficacy of wet snow avalanches in predominantly alpine settings and were conducted in response to a perceived paucity of such measurements. These studies and others (e.g. Rapp, 1959; Ward, 1985; Luckman, 1992; Keylock, 1997; Jomelli and Bertran, 2001) also highlighted characteristic avalanche-created landforms, defined the structure and geometry of dirty avalanche deposits, and discussed the origin of entrained debris and how this relates to rock wall and catchment-wide denudation. Important observations show, for example, that (a) avalanches can readily entrain loose rock fragments and large boulders from their track, which is both a mechanism of instantaneous erosion but also favors long-term denudation by continually exposing fresh rock to weathering (Rapp, 1960; Luckman, 1977); (b) avalanche debris deposits typically have no clear structure or sorting (Jomelli and Bertran, 2001), often consisting of characteristic precariously balanced boulders set down gently during snowmelt with fine sediment and organic material resting on top (Gardner, 1970); and (c) avalanches occurring beneath high mountain crests scour the rock walls below and can help carve narrow and parallel U-shaped gullies (so-called *rasskars*) even in massive rock at locations far above active stream channels (Allix, 1924; Matthes, 1938).

Here we continue the theme of previous studies, again in response to a perceived relative scarcity of measurements quantifying the geomorphic effects of snow avalanches, and in an effort to provide new data on the role of avalanche erosion in alpine mountain belts. We focus on a particular catchment in the southern Swiss Alps, the Guggigraben, where we have measured transported sediment loads and calculated catchment-wide erosion rates over the past 4 years. In addition, we discuss the origin of transported sediment, analyze the debris content of a single, representative avalanche, describe commonalities of dirty avalanche deposits, use numerical runout simulation to predict areas of high velocity and impact pressure most susceptible to erosion, and comment on the distribution and mechanisms of bedrock wear by particle-bed collisions.

Study Area

The Guggigraben catchment is located in the Matter Valley of the southern Swiss Alps (canton Valais; 46.131°N, 7.784°E). The Matter Valley trends roughly north-south over a distance of 25 km between the villages of Stalden and Zermatt; the Guggigraben lies approximately at the mid-point of the valley on the western wall next to the village of Herbriggen (Fig. 1). A number of gullies on the western side of the Matter Valley produce avalanches that periodically reach the valley floor, and which contribute to fan building along with primarily debris flows and landslides. The Guggigraben catchment was selected for our study since it consistently produces dirty avalanches that reach the fan and main valley floor each year in spring. Along with avalanches, debris flows regularly affect the Guggigraben; while we never observed debris flow activity over the 5 years of this study, a debris flow channel with fresh levees cuts through the Guggigraben fan.

Figure 1 shows the Guggigraben catchment outlined on both an aerial photograph and slope map. The contoured slope map was created from a custom 2.5-m-resolution Digital Terrain Model (DTM) generated from aerial imagery; at the time of acquisition there was cloud cover over the highest part of the catchment so

this area lacks elevation data. The total catchment area measured for the Guggigraben is $1.34 \times 10^6 \text{ m}^2$ (Fig. 1); the total fan area is roughly 140,000 m^2 , while the fan area regularly affected by avalanches (evidenced by observation and lack of vegetation cover) is around 33,000 m^2 . The maximum elevation difference from peak to fan apex is around 1900 m over a distance of roughly 2100 m, giving a mean catchment gradient of 0.9 (42°). Bedrock lithologies consist of orthogneiss below about 2300 m a.s.l. and paragneiss and schist above together with bands of orthogneiss. This stratigraphy does not lend itself well to distinguishing the source of avalanche-transported material by lithology alone; only paragneiss and schist boulders can be said to originate from the higher portion of the catchment.

The Guggigraben itself is a ~1000-m-long bedrock gully with average slope of 35°. This structurally controlled incision is particularly straight with a relatively consistent and steep gradient, features which contribute to avalanches regularly reaching the fan and valley (i.e. there are few locations where material is deposited along the track). The gully has four main tributaries that channelize avalanches released higher in the catchment. While the precise avalanche initiation points vary from year to year and are unknown, the slope map (Fig. 1, part b) and area of forest cover (Fig. 1, part a) provide relatively good indication of common initiation areas. These are predominantly located on the southern flank of the Guggigraben above an elevation of ~2200 m, on slopes inclined between 35 and 45°.

Methods

MEASURING TRANSPORTED SEDIMENT LOAD

Our strategy for measuring avalanche-transported sediment volumes evolved slightly from year to year. Common to each measurement, however, was identifying regions of the dirty avalanche deposits with relatively uniform sediment coverage and then sampling the debris content in a number of representative areas within these regions. Measurements were then extrapolated and summed over the entire dirty avalanche deposit in order to quantify the cumulative transported sediment load. Regions of estimated uniform coverage were mapped from field observations and oblique images taken at the time of measurement and transposed to scaled orthophotos. Individual sampling areas ranged in size from 4 m^2 up to 72 m^2 , depending on the sediment content and number of people available for field work, and the total number of sampled areas varied from 20 to 45 per year. Each sampling area was first measured and marked at the corners; we then systematically collected all rock particles until the snow surface was free of debris. We did not sample or account for transported organic material or sediment smaller than gravel. Large boulders everywhere within the deposit (a-axis > 0.5 m) were inventoried separately; their size was measured and volume approximated. The total bulk volume of large boulders was then added to the extrapolated and summed sediment volumes from the representative areas, yielding the total volume of unconsolidated coarse rock debris transported by avalanches each year.

In the first year's measurements (2009), we estimated the volume of debris within each sampling area by measuring the length of the three sides of each larger particle (a-axis > 30 mm) and counting the number of smaller particles (as in Rapp, 1960). Ap-

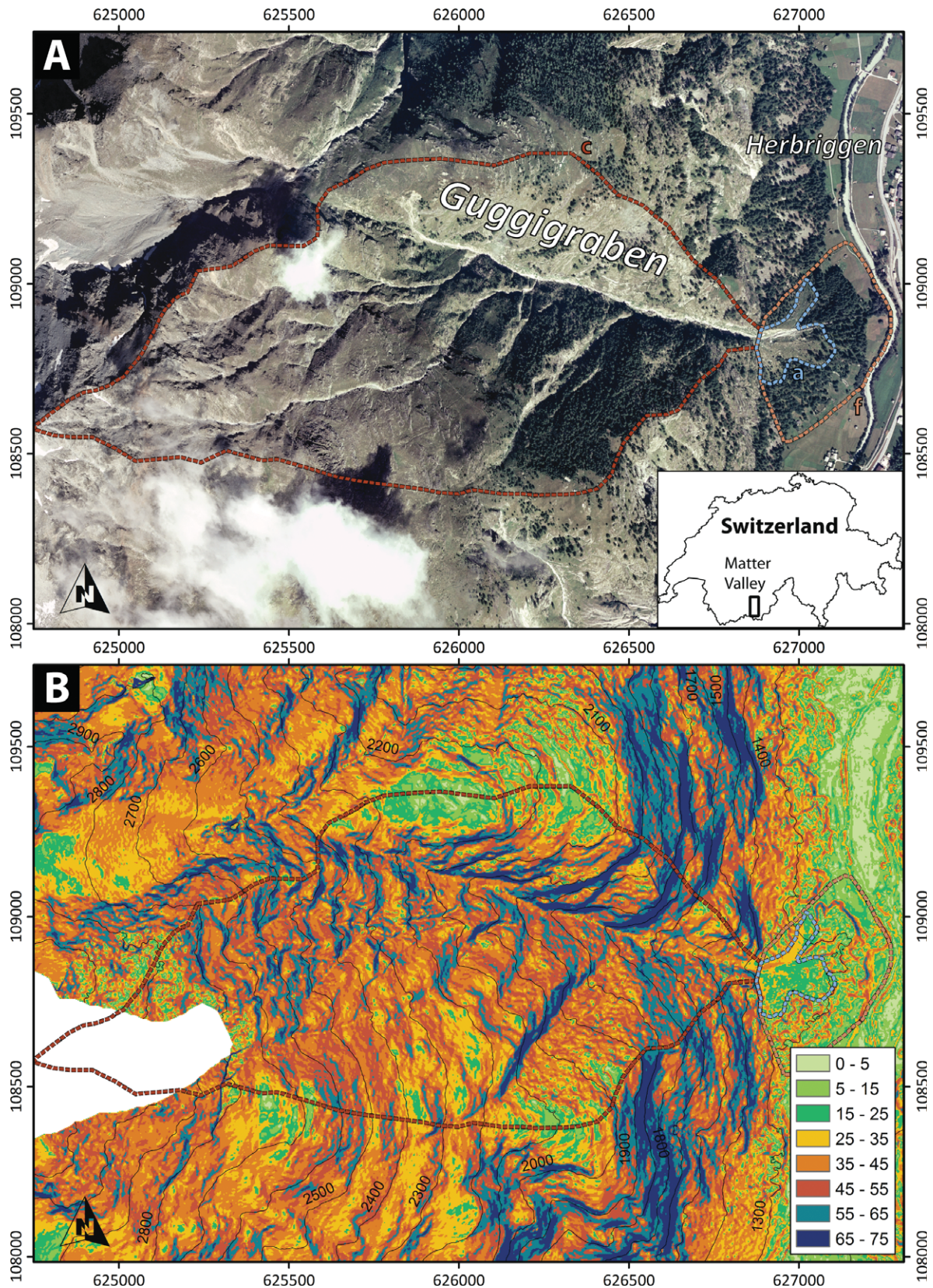


FIGURE 1. (A) Aerial photograph of the Guggigraben catchment and location within the Matter Valley and Switzerland (image source: Swisstopo). The Guggigraben itself is a ~1000-m-long bedrock gully with average slope of 35°. The total catchment area is roughly $1.34 \times 10^6 \text{ m}^2$ (red dashed line, “c”); the total fan area is $140,000 \text{ m}^2$ (salmon line, “f”); while the fan area regularly affected by avalanches (evidenced by observation and lack of vegetation cover) is $33,000 \text{ m}^2$ (blue line, “a”). (B) Slope map (see legend for angles) and 100 m contours. Elevation data are from a custom 2.5-m-resolution Digital Terrain Model (DTM) generated from aerial imagery; at the time of acquisition there was cloud cover obscuring the highest part of the catchment. Coordinates are in meters of the Swiss grid system.

proximating each rock as a rectangular cuboid, we determined individual intact rock volumes from size measurements. For the smaller particles, we estimated an average size in order to calculate volume, and then multiplied by the total number of particles. We summed intact rock volumes and then corrected for the density change from intact rock to unconsolidated debris using a bulking factor of 1.5 (assuming intact rock density = 2700 kg/m^3 and debris density = 1800 kg/m^3). In 2010, we streamlined our technique by measuring the mass of transported sediment within each sampling area; we retained this method thereafter. After cleaning the snow surface, all rocks were placed into a bucket and weighed. Larger particles that would not fit into the bucket were measured for size and their mass calculated using the intact rock density above. The sediment volume in each sampling area was then determined from the total mass assuming an unconsolidated debris density of 1800 kg/m^3 , and the average deposited sediment thickness calculated by dividing volume by sampled area. Since a number of sampling areas were usually located within a given region of uniform sediment coverage, we determined the mean thickness value for each region. Finally, multiplying this mean thickness by the area of the avalanche deposit belonging to each region, and summing over the entire fan, we calculated the cumulative transported sediment volumes.

Although every effort was made to ensure a consistent sampling area from year to year, the extent to which dirty avalanche deposits were investigated within the bedrock gully above the fan's apex varied, in part due to safety considerations. In 2009 and 2010, measurements were made only on the fan and within the gully around the apex, and results had to be extrapolated into the higher areas of the gully to cover the total extent of observed deposits. In 2011 and 2012, dirty avalanche deposits were characterized throughout their extent, even in the higher parts of the gully; typically the deposits had a clear upper boundary located at a small bedrock step. The measurement technique used in 2009 (measuring volume) was likely subject to greater error than that used in subsequent years (measuring mass). We approximated each block as a rectangular cuboid (based on assessment of typical block shapes), and made efforts in the field to avoid overestimating volumes by measuring effective cuboid dimensions; however, the final values may still be greater than had we assumed other shapes. While our measurement technique evolved over time, we estimate in light of overall uncertainty that our transported sediment measurements are accurate to within $\pm 20\%$.

Key to a successful measurement was observing the timing and frequency of dirty avalanches and thus knowing when to make measurements. In the first 2 years, we made many measurements late in the season, but longer than anticipated ongoing avalanche activity complicated extrapolation. In the final 2 years we adopted a more pragmatic approach, making end-of-season sediment load measurements at a carefully timed moment. The appropriate sampling time followed not long after the last dirty avalanche of the season, at a time when snowmelt had concentrated most of the debris on top of the snow surface, but when snowmelt had not progressed so far that the material was lying on the fan and could not be conclusively linked to that year's avalanche cycle. Each year we also dug a small $\sim 1\text{-m}$ -deep pit in the dirty avalanche deposits to verify that the majority of sediment was located at the snow surface, and each year this was confirmed.

RUNOUT SIMULATION

Avalanche erosion is predicted to be most efficient in regions where the track experiences high runout velocities and impact pressures. However, not all portions of the track are accessible, and direct observation of avalanche movement was rare; we thus used numerical simulation to predict runout dynamics for a presumed typical event. The avalanche simulation software RAMMS::Avalanche was created to provide engineers with a versatile tool to analyze avalanche flow problems that cannot be addressed with existing one-dimensional models (Christen et al., 2010a). RAMMS solves the depth-averaged equations governing avalanche flow over complex 3D terrain with accurate second-order numerical solution schemes (Christen et al., 2008). The model allows specification of multiple release zones and predicts avalanche runout dynamics, flow velocities, flow depths, and impact pressures (Christen et al., 2010b). RAMMS employs the established and well-calibrated Voellmy friction model (Voellmy, 1955), which is described by two parameters: dry Coulomb friction (μ) and velocity-squared dependent turbulent friction (ξ). Frictional parameters are calculated automatically based on analysis of the input terrain model and specified return interval, and can be manually adjusted to account, e.g. for the presence of forest. Swiss guidelines for suggested friction parameters are available from Salm et al. (1990).

Our simulation was designed to capture the typical behavior and characteristics of a representative wet snow avalanche occurring each spring during our study. Based on field analysis of potential avalanche flow paths and likely starting zones, we selected a release area on the southern flank of the Guggigraben catchment (see Fig. 6 later in this paper). We manually created a release area of roughly 3620 m^2 and specified a mean release depth of 0.9 m (based on typical crown heights). RAMMS then computes the total released volume based on the inclination of topography and DTM resolution (here 2.5 m); our avalanche had an initial volume of 4710 m^3 . No erosion of underlying snow was allowed during runout. Friction parameters were determined automatically in RAMMS based on local terrain roughness and our delineation of forested regions (for details see Egloff, 2010). In order to achieve the best fit to observed deposition patterns, we increased the Coulomb friction parameter from 0.49 in the lower gully (automatically determined) to 0.52 within the fan's main channel. For density, we selected a value of 250 kg/m^3 , which is on the lower end of expected density values for wet snow avalanches (Hopfinger, 1983).

Results

Dirty avalanche activity at the Guggigraben was concentrated between the middle of March and the middle of April, during the period of rapid spring snowmelt. However, the exact timing of events varied considerably from year to year depending on the amount of preceding snowfall and the rate of snowmelt. From analysis of deposits and speaking with local land owners, we identified between 2 and 8 dirty avalanches per year at the Guggigraben (end members in 2011 and 2012, respectively; see Table 1), although these numbers likely represent minimum values since some avalanches may have been missed. Visits to the field area in late fall also revealed dirty avalanche activity in nearby catchments, indicating that early winter events are also possible; the criterion of a

TABLE 1
Summary of transported sediment load measurements from four years at the Guggigraben.

Year (spring)	Number of dirty avalanches ¹	Total sediment volume (m ³)	Catchment erosion rate ² (mm/a)	Avalanche deposit area (m ²)	Mean deposit thickness (mm)	Cumulative snowfall (cm)
2009	5	70	0.052	16220	4.31	405
2010	3	23	0.017	7045	3.31	168
2011	2	15	0.011	4590	3.18	135
2012	8	35	0.026	9159	3.82	178

¹ May be minimum values.

² Catchment area = 1,336,000 m².

partially snow-free substrate is met. Figure 2 shows photographs of the Guggigraben fan at the end of each avalanche season during the 4 years of observation. We encountered considerable variability in the quantity of avalanche deposits; 2009 featured high avalanche activity, while in 2010 and 2011 there were only 3 and 2 dirty avalanches, respectively. The fan's main channel is visible in the

middle-right foreground of Figure 2; not clearly visible is an older, now-abandoned channel (see 2009 deposits on the left side of the photo) that also fills with avalanche deposits. After filling the channels, avalanches either spill out to the north, through a clearing in the forest to the valley floor (see Fig. 1) or cover the fan surface (Fig. 2). Deposits also extend into the bedrock gully above the fan



FIGURE 2. Photographs of the Guggigraben fan and bedrock gully outlet at the end of each avalanche season, illustrating spatial and temporal variability in the distribution of dirty avalanche deposits. Photos are from 18 April 2009, 29 April 2010, 13 April 2011, and 18 May 2012. An additional debris-rich avalanche occurred after the 2010 photograph depositing material near the fan apex (compare with Fig. 4). Sediment debris density is not always apparent from the color of deposits alone, which often better reflects organic material content. Deposits preferentially fill the fan's main channel first and then spill out covering other areas of the fan.

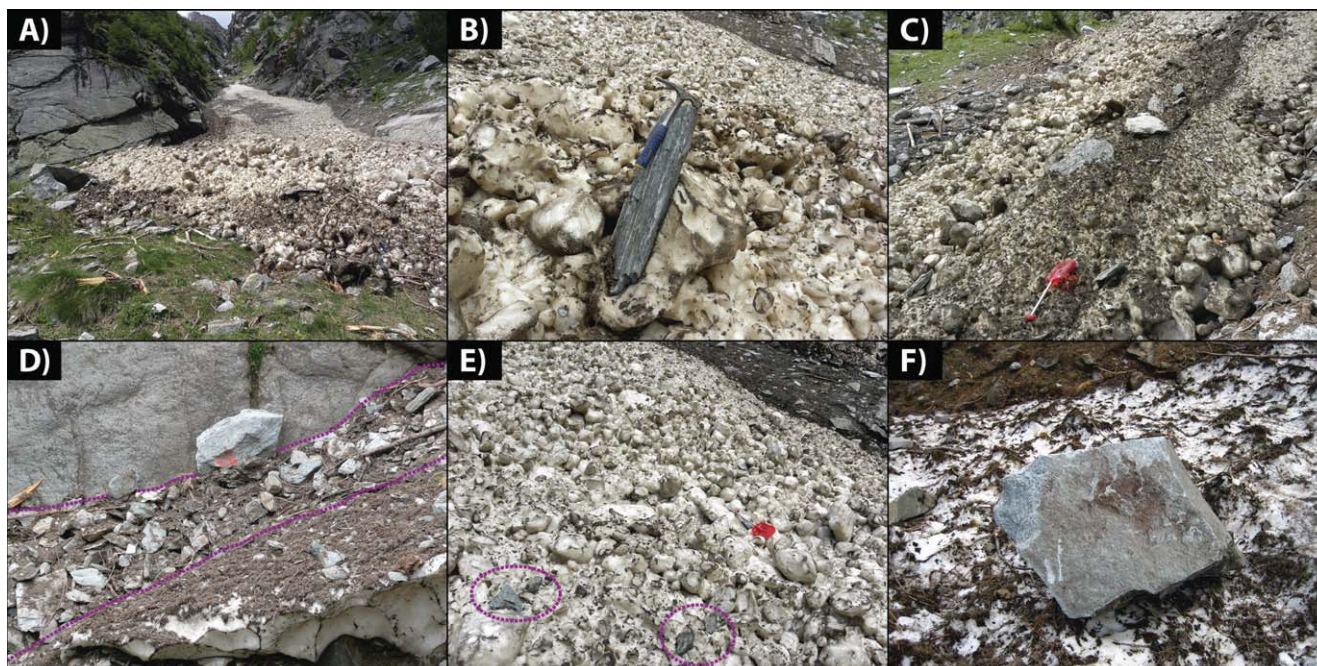


FIGURE 3. Typical features of dirty avalanche deposits: (A) Looking up the Guggigraben from near the fan apex (spring 2010); boulders and tree branches transported by avalanches can be seen on the fan surface and within the melting deposit. (B) Large boulder transported by a dirty avalanche; note also the characteristic “snowball” structure of the deposit. (C) Dirty avalanche deposits filling the main channel on the fan (2010), with a high density of debris deposited in the foreground. (D) Within the bedrock gully above the fan, sediment can become concentrated along the gully walls during snowmelt; see outlined region (2011). Boulder #20 shown was initially deposited with flat face upward, and migrated to the channel wall and was overturned during snowmelt; the boulder is roughly 90 cm long. (E) Typical “snowball” structure and appearance of dirty avalanche deposits; four large boulders are circled (see shovel for scale). (F) Large boulder transported by a wet snow avalanche in spring 2009; the boulder is 89 cm long and shows signs of impact during transport.

apex; about 100 m into the gully a bedrock step typically delimits the zone of deposition.

Dirty avalanche deposits had a characteristic snowball structure consisting of decimeter-sized agglomerations of packed snow and ice (Fig. 3, parts A and E). Direct observation revealed that this structure is well established by the time the moving avalanche reaches the mouth of the bedrock gully and fan apex. Interspersed within the deposits are varying quantities of organic and inorganic debris. Deposited material ranged from tree branches, pine needles, and intact soil parcels, to gravel, cobbles, and boulders up to 1 m^3 (Fig. 3, parts B and C). The debris content of individual avalanche deposits was highly variable, and some deposits took their characteristic dark color from high organic content even in the absence of significant sediment. Larger boulders were generally angular and fresh, with distinct rounding of corners caused by impacts during transport (Fig. 3, parts B and F). As the avalanche deposits melted, entrained sediment was set down gently, often resulting in precariously balanced boulders with assorted debris on top. Since most avalanche deposits were laterally convex, larger rocks had a tendency to melt free and slide to the sides of the lobe, where they became concentrated in bands on the sides of the main channel (Fig. 3, part D). In flat-lying areas, gradual snowmelt resulted in sparse sediment deposits with no clear structure or sorting, giving an appearance of randomly distributed boulders lying on the otherwise grassy fan (Fig. 3, part A). Painted marker stones used to investigate debris entrainment on the fan showed no movement. Rather, we found that the fan surface was usually protected either

by winter snow or older avalanche deposits, which provided a smooth basal shear surface for new events. Personal observation of one avalanche indicated a velocity of 5–7 m/s within the bedrock gully immediately above the fan.

Identified regions of uniform sediment coverage for 2010, 2011, and 2012, and their mean deposit thickness, are shown in Figure 4; as determined from measurements in a number of individual sampling areas (see Section *Measuring Transported Sediment Load*). Deposited sediment thickness ranged from $<1 \text{ mm}$ to 18 mm, with typical values around 1–5 mm each year. The thickest sediment accumulation occurred within the fan’s main channel near the apex and in the bedrock gully immediately above. Table 1 lists the cumulative annual transported sediment volumes at the Guggigraben for the 4 years of observation, found by summing the measurements shown in Figure 4. Results reveal transported sediment volumes of 70 m^3 in 2009, 23 m^3 in 2010, 15 m^3 in 2011, and 35 m^3 in 2012. When distributed over the entire catchment area of $1.336 \times 10^6 \text{ m}^2$, these volumes correspond to catchment erosion rates of approximately 0.05, 0.02, 0.01, and 0.03 mm/a, respectively. The mean thickness of deposits, found by dividing the total transported volume by cumulative deposit area, is relatively consistent from year to year (despite large differences in volumes), averaging roughly 3.5 mm. In 2011, we were able to investigate one dirty avalanche in detail shortly (4 days) after deposition. We measured a total snow volume of roughly 9900 m^3 and a transported sediment volume of 8 m^3 , giving a volumetric sediment content of 0.08% and a mean deposit thickness of 1.3 mm. Our observations

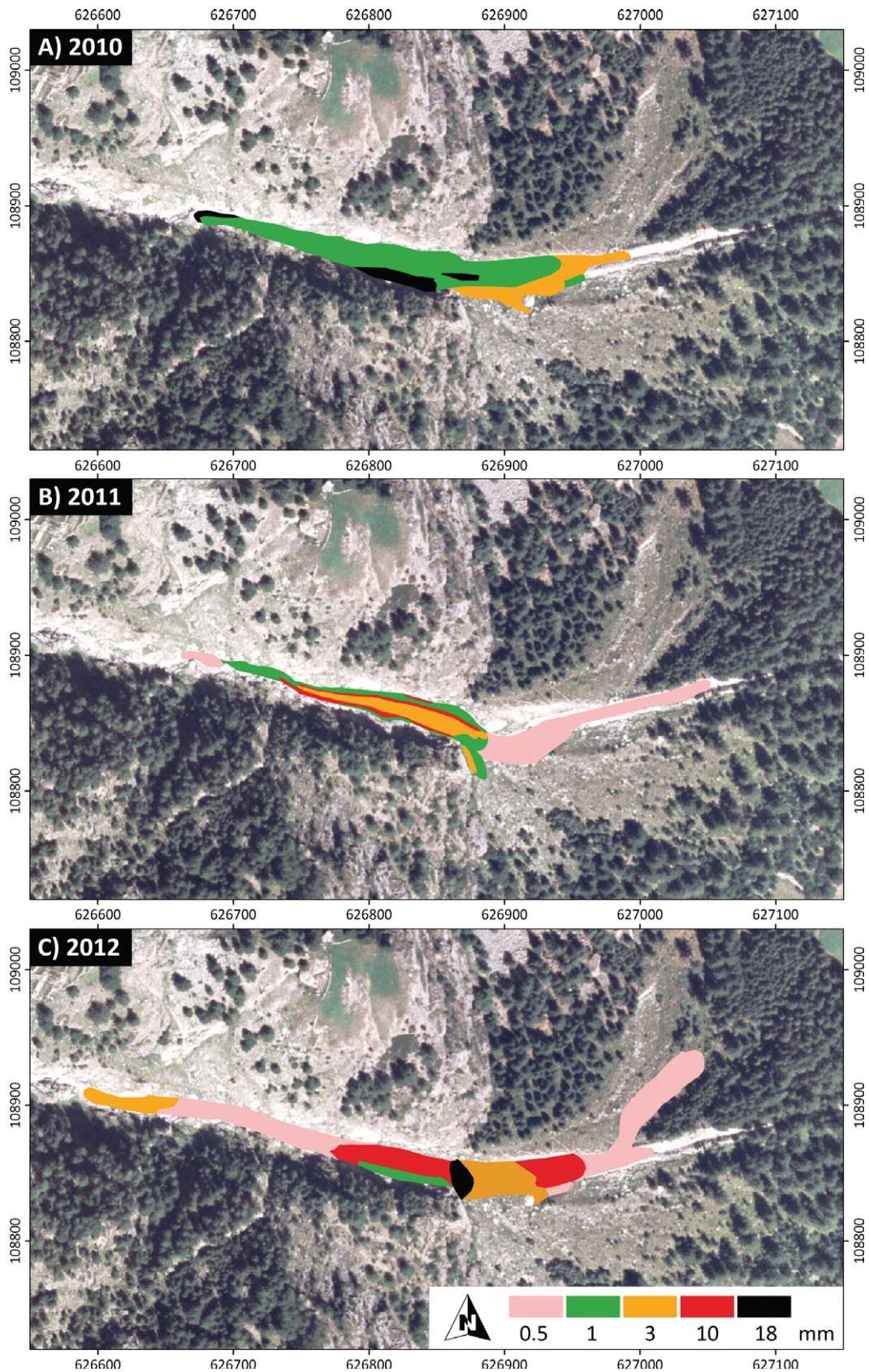


FIGURE 4. Accumulation of avalanche-transported sediment in (A) 2010, (B) 2011, and (C) 2012 (no map available for 2009). Shown are mean sediment accretion values (see legend in C) for each region of estimated uniform coverage. Deposited sediment thickness varied considerably from year to year, due in part to changing dirty avalanche frequency and the distribution of preceding avalanche deposits, dirty or clean. The thickest sediment accumulation preferentially occurred in the fan's main channel near the apex and within the bedrock gully above.

suggest these values are representative of other dirty avalanche events at the Guggigraben. Annual inventories of large boulders (a-axis > 0.5 m) showed between 20 and 40 boulders transported each year, which constitute roughly 20% of the annual sediment load.

Within the bedrock gully above the fan, signs of abrasive and collisional wear were evident on gully walls high above the active stream channel. These included scoured and rounded bedrock surfaces with moss and lichen growing preferentially on the lee side of protrusions, fresh signs of boulder impacts, and scratch marks on the rock walls (Fig. 5). Since the channel was filled by previous winter avalanches, springtime dirty avalanche events had a characteristic zone of influence, eroding the rock walls many meters above the thalweg (Fig. 5, part A). A general lack of vegetation on these surfaces indicates recurring scour by dirty avalanches. Similarly, precariously balanced sediment deposited on steep rock surfaces and high ledges (Fig. 5, part B) provides clear evidence that these walls are subject to particle-bed contact during dirty avalanches each year. Scratch marks (oriented both vertically and down-channel), as well as impact marks, could be found throughout the lower reaches of the Guggigraben gully (Fig. 5, part C). These are direct evidence of bedrock erosion by dirty avalanches as entrained boulders strike the walls; each individual impact or scratch removed fractions of a millimeter of bedrock. Protruding facets were especially vulnerable to avalanche wear.

Results of our numerical runout simulation are presented in Figure 6, parts A and B, where the predicted maximum velocity and maximum impact pressure are shown for each point along the avalanche runout path. Following initial release, the avalanche quickly accelerates down steep slopes ($\sim 45^\circ$) and becomes channelized; here maximum predicted velocities are in excess of 30 m/s and maximum pressures reach nearly 250 kPa. Impact pressures are calculated as ρv^2 , where ρ is density and v is the avalanche flow velocity (McClung and Schaerer, 1993). Field inspection of this area revealed clear signs of avalanche damage and erosion; a bent trail sign and scoured bedrock were found in the precise area of predicted maximum pressure and velocity (Fig. 6, parts C and D). Avalanche runout continues down the tributary channel, branching at one point before reaching the main Guggigraben gully. In the final part of its transit, the avalanche is tightly channelized in the Guggigraben, following the thalweg at velocities of 10–15 m/s. Flow heights are around 1–2 m. At the mouth of the gully, avalanche velocities slow to around 5–10 m/s, which is in good agreement with personal observation of one avalanche event in this area. The avalanche then comes to rest on the fan, filling the main channel with deposits between 0.5 and 1.5 m thick. The thickest deposits are located at the fan apex and reach nearly 2 m, values which are in good agreement with our field observations. The final deposit geometry matches well with our observations and measurements, and the simulated volume of $\sim 5000 \text{ m}^3$ is representative of a typical springtime dirty avalanche at the Guggigraben.

Discussion

Wet snow avalanche activity at the Guggigraben was concentrated between the middle of March and the middle of April, during the period of rapid spring snowmelt. Related studies also show this common result of predominant wet snow avalanche timing in late

spring (e.g. Baggi and Schweizer, 2009). Dirty avalanche activity proceeded contemporaneously with wet snow avalanches, albeit usually with a slight time lag of a week or more as the ground along the runout tracks became increasingly snow free. Mean sediment accretion rates in the avalanche deposition area at the Guggigraben are similar to other reported values from North America, Europe, and the Himalaya, which generally lie in the range of a one or a few millimeters per year (Gardner, 1983; Luckman, 1978; Keylock, 1997; Heckmann et al., 2005). Sediment deposition rates are notably consistent from year to year (Table 1), despite large differences in transported volumes and in contrast to that of other processes affecting fan morphology, such as debris flows with more intermittent occurrence. In general, most dirty avalanches came to rest near the apex of the fan and in the adjacent bedrock gully above (Fig. 3), making this the area of greatest sediment accumulation (Fig. 4).

The volume of transported sediment ($\sim 8 \text{ m}^3$) measured in our analysis of a single dirty avalanche in 2011 is similar to other reported values from around the world for individual events (Rapp, 1960; Luckman, 1978; Gardner, 1970, 1983; Ackroyd, 1986; Bell et al., 1990). However, this value can vary considerably between events and catchments (among other things), and perhaps more useful is to discuss the volumetric sediment content, which in our case was around 0.1%. Other authors have reported sediment concentrations between 0.01 and 1% (e.g. Gardner, 1970, 1983), which nicely bracket our measured value. Based on our field observations, we consider it likely that a typical dirty avalanche at the Guggigraben carries around 0.1% rock debris by volume, of which we estimate $\sim 20\%$ are boulders > 0.5 m. An average spring season may see around 5 such dirty avalanche events with varying volume, transporting in total $\sim 30 \text{ m}^3$ of rock debris and ~ 30 large boulders. These numbers can provide a useful basis for future efforts to model long-term rates of sediment deposition or bedrock gully erosion.

Typical avalanche sediment deposits had no characteristic grain size sorting or vertical/lateral structure, a feature commonly observed by other researchers (Rapp, 1960; Jomelli and Bertran, 2001; Freppaz et al., 2010). The only depositional patterns we discovered arose from remobilization of debris during snowmelt. In these cases, large boulders had a tendency to slide down or to the side of the deposits until reaching the boundary with the snow-free surface. In some cases this could lead to characteristic patterns of sediment deposition at the avalanche margins (Fig. 2, part D). However, in most cases, boulders and gravel alike were set down gently and randomly on the fan surface, mixed with tree branches, soil parcels, and pine needles. Indeed, the characteristic appearance of an avalanche-affected fan in the Matter Valley is that of randomly distributed large boulders (often precariously balanced) on the grassy fan surface, commonly with gravel particles and plant debris resting on top (Luckman, 1977). Similar precariously balanced boulders high on rock ledges within the bedrock gully are also characteristic indicators of dirty avalanche activity. Boulders up to 1 m^3 or more can be transported, although an upper size limit could not be identified from our work.

Shallow pits dug in avalanche deposits revealed that the majority of entrained sediment lay on top of the snow surface or within a narrow surficial zone. This phenomenon has also been observed by other researchers (e.g. Rapp, 1960; Gardner, 1970; Bell et al., 1990; Jomelli and Bertran, 2001); however, it remains unclear

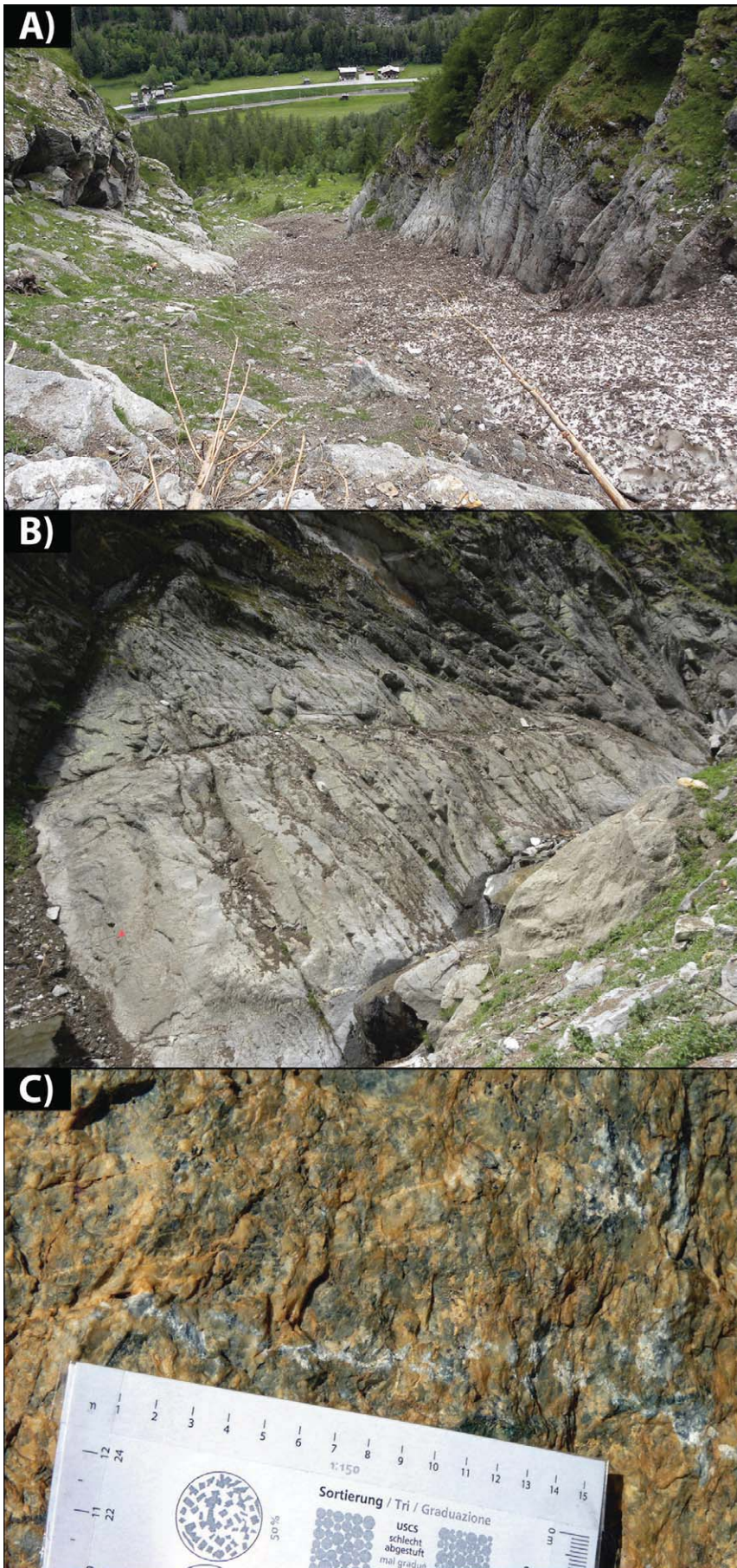


FIGURE 5. Signs of bedrock erosion by dirty avalanches. (A) Looking down the Guggigraben, dirty avalanche deposits fill the channel up to 10 m above the thalweg. Signs of wear are especially evident on the southern gully wall (middle-right in photo), as seen by the smoothed bedrock texture and lack of moss or vegetation on scoured surfaces. (B) Looking up from the fan to the southern wall of the Guggigraben, freshly eroded bedrock is evident by its light color in contrast to more weathered surfaces. New sediment has been deposited by melting snow even on these steep rock slopes. Moss and vegetation grow on the walls above the reach of avalanches. (C) Direct evidence of bedrock erosion by dirty avalanches: scratch mark (above the scale) and impact mark (upper right) (note on the scale shown 1 unit = 6.67 mm). These features are located several meters above the stream channel and were identified shortly after snowmelt.

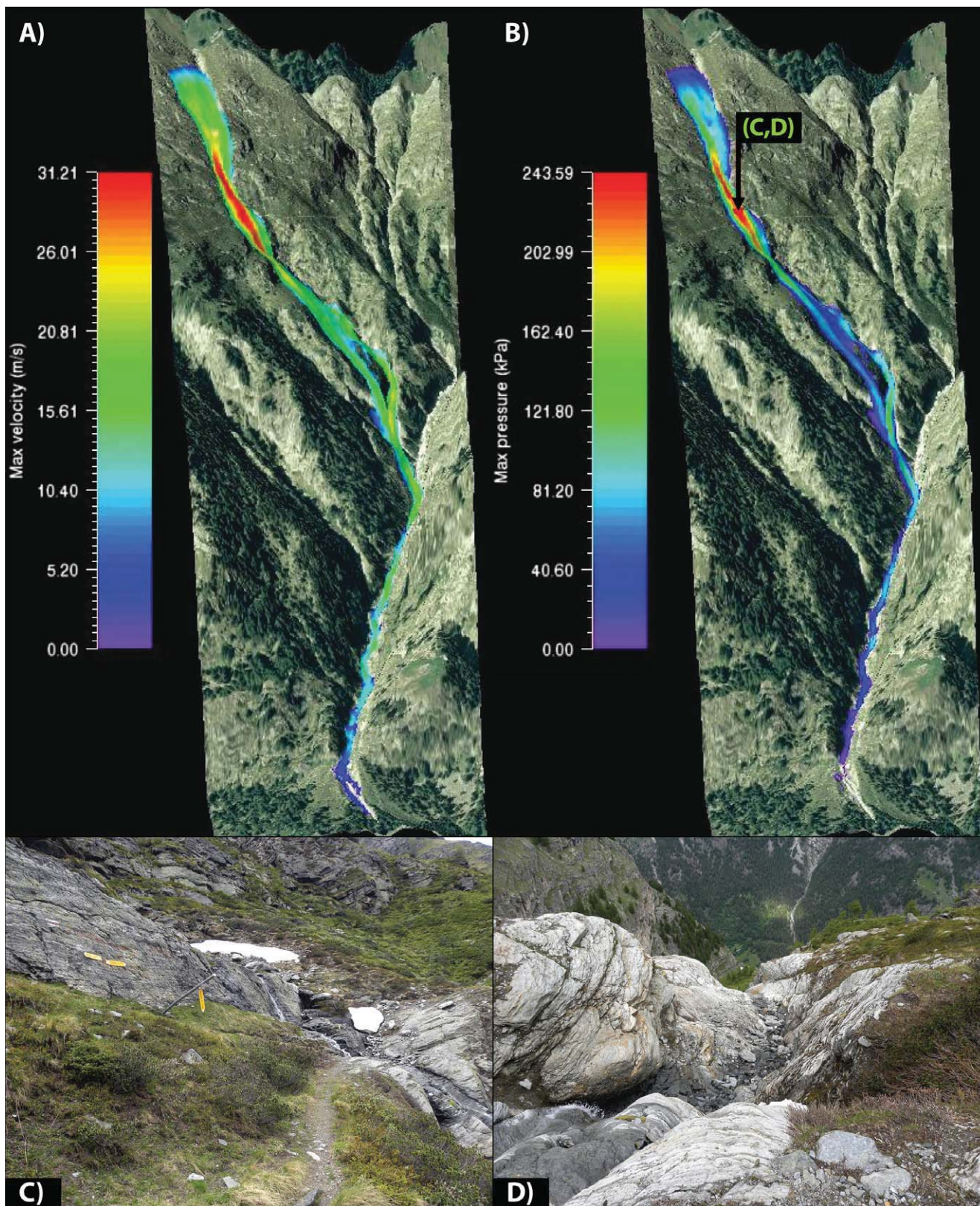


FIGURE 6. RAMMS simulation outputs and comparison with field observations. (A) Maximum velocity distribution from avalanche initiation to final deposition; (B) maximum pressure distribution; (C) bent sign post along the avalanche track at the point of maximum predicted velocity and pressure (see location in B); (D) Scoured bedrock at the same location of maximum velocity and pressure.

whether stratification arises during transport or the final phases of deposition, or if it is simply a consequence of melt concentration. Our observations show that freshly deposited sediment was either mixed with or attached to individual snowball agglomerations (Fig. 3, part B), and that large boulders were commonly lying on the snow surface. A cross section dug through one avalanche 4 days after deposition showed that the majority of sediment lay near the top of the deposit. Snow pits encountering multiple events also showed apparent stratigraphy, with a debris-rich surface followed by clean snow interior repeated at depth. This phenomenon is certainly enhanced by snowmelt between successive events, but we cannot ascertain whether there is natural stratification that arises during flow. We do point out, however, that freshly transported sediment was predominantly interspersed with the snowball features in wet snow avalanche deposits. Such features are suggested to preferentially occur in the upper part of an avalanche (Jomelli and Bertran, 2001), above a highly sheared basal snow layer, possibly leading to coarse stratification of deposits. Gardner (1970) also proposed that the formation of snowballs, and their interaction with the ground surface, is important for debris entrainment.

The cumulative volume of sediment transported from the Guggigraben varied significantly from year to year (Table 1). To investigate climatic controls on avalanche debris transport, we analyzed snow height measurements from a nearby weather station at Graechen (1550 m a.s.l., 9 km distant). Figure 7, part A, presents daily snow height measurements spanning the 4 years of our study. These data show significant annual differences in snowfall, especially the winter of 2008–2009 which experienced greater snowfall than the following three winters; the first snows fell earlier, stayed high throughout winter, and melted later in spring. In 2009 we also measured the greatest volume of sediment transported by dirty avalanches at the Guggigraben (Fig. 3). Figure 7, part B, presents the cumulative annual snowfall at Graechen for each of the 4 years of our study, found by summing daily snowfall measurements over the winter season. When compared with transported sediment loads, a clear trend arises; avalanche sediment transport scales directly with cumulative annual snowfall. This result is intuitive yet unexpectedly simple; many other factors can control the occurrence of dirty avalanches, such as the rate of spring warming, late season precipitation, snowpack morphology, etc. However, our measurements reveal a relatively straightforward relationship—that cumulative annual snowfall alone may be a good predictor of avalanche-transported sediment volumes (for an opposing view, see Sass et al., 2010, and Luckman, 1978). We rationalize simply that a greater amount of snow lying on the hillslope at the end of each winter translates to a greater flux of wet snow avalanches through the Guggigraben in spring, when the gully and surrounding hillslopes are only partially snow covered. The greater spring avalanche flux creates greater opportunity for debris entrainment and transport, leading to increased rates of sedimentation on the fan. Additional data may help clarify this trend.

Periodic impacts by entrained boulders in dirty avalanches cause wear to bedrock walls of the Guggigraben. A similar process is thought to help carve shallow furrows in steep rock walls (Allix, 1924; Matthes, 1938); however, it is less widely discussed as a mechanism of channel incision at lower altitudes (McCoy et al.,

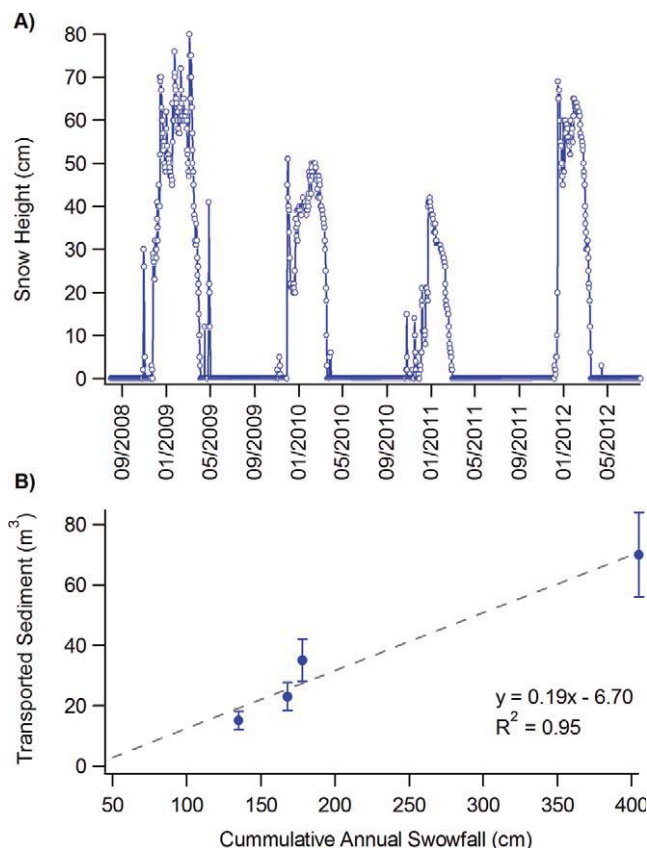


FIGURE 7. (A) Daily snow height measurements from a nearby weather station at Graechen (1550 m a.s.l., 9 km distant) during our period of observation (data courtesy of MeteoSwiss). The winter of 2008–2009 had significantly greater snowfall than the following two winters. (B) Total transported sediment (see Table 1) plotted against cumulative annual snowfall for each of the four years of observation. Although the data are limited, results indicate good correlation between annual sediment transport and cumulative snowfall. The dashed line indicates the best linear fit, with equation and R^2 value shown in the inset. Error bars are $\pm 20\%$.

2009). Field observations in the Guggigraben revealed a number of impact and scratch marks on the gully walls, direct evidence of bedrock erosion by avalanches. Although these marks were widespread and easily discovered each year, they were not ubiquitous; e.g. a number of painted rock surfaces showed no wear over 2 years of observation. Each rock impact or scratch mark represents millimeters or fractions of a millimeter of bedrock erosion, a small amount compared to other forms of primary detachment (e.g. rock-fall). However, in certain catchments such as the Guggigraben, avalanche erosion is regularly repeated each year. Unique to avalanche wear is the characteristic zone of influence; because the channel is filled with snow in winter and spring, avalanches erode the bedrock walls many meters (up to 10 m) above the active stream channel. This action will, over time, lead to widening of the channel as compared to fluvial incision alone. Evidence of the cumulative erosive action at the Guggigraben is the freshly scoured and unvegetated nature of the bedrock gully walls (Fig. 5, parts A and B). Our results also show that bedrock channel erosion is possible in higher areas of the catchment (Figure 6). Typical avalanche flow velocities in the lower part of the gully are 5–10 m/s, as revealed

by our numerical simulation and direct observation (comparable values are reported by Hopfinger, 1983). These are then also the approximate impact velocities, although the boulder incidence angle can vary from nearly orthogonal to highly oblique. Mechanistic prediction of bedrock erosion by boulder impacts in dirty avalanches is as yet beyond the outcomes of this work. However, our results do serve to add useful parameterization of unknown variables, such as impact velocities, the number and size of entrained boulders, and the typical amount of bedrock wear expected per impact.

Catchment erosion rates determined in this work vary between 0.01 and 0.05 mm/a. These values are similar to erosion rates reported for dirty avalanches by Sass et al. (2010) (also in the European Alps); however, these authors believed their values were higher than normal because the catchment was affected by a wildfire. We find no reason to suspect our values are abnormally high, i.e. no short-term disturbance such as a fire; however, we do point out that they are relatively high compared to other tributary catchments in the Matter Valley. The Guggigraben is particularly susceptible to avalanche erosion because of its steep mean catchment gradient and straight and steep main gully, which efficiently funnels avalanches and their sediment load to the fan and valley river system. Other steep catchments in the Matter Valley are similar, while those with large steps in their longitudinal profiles do not have avalanche-transported sediment reaching the valley floor. In the Matter Valley, catchment-wide erosion rates of ~ 0.7 mm/a have been estimated from modern (~ 30 years) river sediment discharge measurements (Schlunegger and Hinderer, 2003). In comparison with our measured values at the Guggigraben (an order of magnitude lower), avalanche erosion appears to play a relatively minor role in overall catchment denudation. However, our observations show that avalanche erosion at the Guggigraben is *locally* significant (as in Rapp, 1960) under current climatic conditions. During the Holocene, as local temperatures and precipitation patterns changed through time, other steep tributary catchments along the Matter Valley may have been similarly affected, while dirty avalanche activity at the Guggigraben likely varied.

Conclusive evidence revealing the source of avalanche-transported sediment at the Guggigraben was rare. However, we note that the main and tributary channels are filled with abundant loose, angular rock debris, similar to that found in avalanche deposits, which originates first from rockfall or landslides. Active landslides were also identified in the upper portion of the main gully. We therefore believe that most transported sediment originates from within the gully, entrained by wet snow avalanches during their transit, rather than by primary detachment from the hillslope. Our numerical simulation serves to highlight areas in the channel with high velocity and impact pressure where sediment entrainment may be most likely (Fig. 6). These occur preferentially below steps in the longitudinal profile and at the confluence of the tributary and main gully, where high velocities and downward-plunging impact vectors make snow and substrate erosion probable. Most transported sediment was then deposited in the area around the mouth of the bedrock gully and fan apex (Fig. 4) where it either accumulates contributing to long-term fan building or is later remobilized by periodic floods and debris flows. Avalanches at the Guggigraben thus play an important role in transporting sediment from interme-

diate storage sites higher in the catchment to the main valley fan and river system.

Conclusion

Four years of measurements at the Guggigraben catchment in the Matter Valley, Switzerland, allow us to comment on typical volumes and depositional patterns of sediment transported by springtime wet snow avalanches. Cumulative mean annual sediment loads vary between ~ 15 and 70 m³/a, values which appear to be directly correlated with the total annual winter snowfall. Individual dirty avalanches carry around 0.1% rock debris by volume, of which $\sim 20\%$ are boulders >0.5 m. A typical spring may see around 5 such dirty avalanche events, transporting as part of their sediment load ~ 30 large boulders up to 1 m³ in size. Mean sediment accretion rates are in the range of 3 – 4 mm/a, with most deposited material concentrated near the fan apex. The typical appearance of avalanche sediment deposits at the Guggigraben is that of randomly distributed boulders set down loosely and gently on the fan surface, commonly with gravel and plant debris resting on top. Similar precariously balanced boulders on rock ledges within the bedrock gully are characteristic indicators of dirty avalanche activity. Results of our numerical runout simulation indicate maximum flow velocities of ~ 30 m/s and impact pressures of ~ 250 kPa, the locations of which match well with field observations of scour and impact damage. We observed direct evidence of bedrock wear and erosion by dirty avalanches, produced by impacts and abrasion of entrained boulders against the gully walls during flow. The cumulative erosive action leads to widening of the channel over time, as compared to fluvial incision alone. Bedrock scour is prevalent in the lower reaches of the gully near the fan apex, but also common in higher areas as dictated by channel geometry. Measured catchment-wide erosion rates at the Guggigraben vary from 0.01 to 0.05 mm/a, which are a relatively minor contribution to overall denudation of the Matter Valley. However, dirty avalanches are locally significant and occur regularly at the Guggigraben, efficiently transporting sediment each year from the upper reaches of the catchment to the valley floor and main river system.

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