The Influence of Frost Weathering on Debris Flow Sediment Supply in an Alpine Basin

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Abstract Rocky, alpine mountains are prone to mass wasting from debris flows. The Chalk Cliffs study area (central Colorado, USA) produces debris flows annually. These debris flows are triggered when overland flow driven by intense summer convective storms mobilizes large volumes of sediment within the channel network. Understanding the debris flow hazard in this, and similar alpine settings, requires determining the magnitude of sediment accumulation between debris flow seasons and identifying the control on sediment production. To address these knowledge gaps, we measured changes in sediment production using a sediment retention fence to quantify how sedimentation was influenced by temperature at the plot scale. These measurements were extrapolated to a larger area, where we extended the sediment fence results to explore how rockfall sedimentation contributed to channel refilling between active debris flow periods. This work shows that debris flow channel refilling is correlated with low temperatures and time in the frost-cracking window, implicating frost-weathering mechanisms as a key driver of sedimentation. This sediment production process resulted in a large amount of sediment accumulation during a single winter season in our study reach (up to 0.4 m in some locations). Using these observations, we develop a channel refilling model that generally describes the mass balance of debris flow watersheds in alpine areas.

1. Introduction

Debris flows are mixtures of water and unconsolidated sediment that flow quickly downhill and pose a natural hazard for infrastructure and human life (Major & Iverson, 1999). Unlike floods, which are extreme water-dominated flow events that breach the natural channel boundaries, debris flows incorporate more than 40% sediment by volume and move with greater velocity and depth than flood-dominated flows (e.g., Kean et al., 2016). The likelihood that a debris flow will be triggered depends on the availability of (1) sufficient precipitation and (2) sediment (Bennett et al., 2014; Church & Miles, 1987). A large body of literature documents the precipitation thresholds required to generate debris flows regionally (Berti et al., 2000; Cannon et al., 2008; Coe et al., 2008; Staley et al., 2012; Shieh et al., 2009; Wieczorek et al., 2000; Wilson & Wieczorek, 1995) and globally (Caine, 1980; Guzzetti et al., 2008). However, fewer studies have investigated how debris flow channels refill with sediment between events (e.g., Bennett et al., 2014). The initial source of sediment needed to generate a debris flow can arise from different parts of a landscape. For example, debris flows can be initiated by landslides (Iverson et al., 1997), en masse failure of channel bed sediment (e.g., Kean et al., 2013; Takahashi, 1978, 1981), or a progressive bulking of sediment in overland flow (e.g., Cannon, 2001; Meyer & Wells, 1997). At the basin scale the total debris flow volume is largely controlled by the volume of material entrained in the debris flow channel rather than the initial volume of material that fails (Brayshaw & Hassan, 2009; May, 2002; Santi et al., 2008; VanDine & Bovis, 2002). Consequently, the volume of a new debris flow depends on the amount of available material stored in channels.

Sediment availability in steep mountain channels depends on whether a watershed is transport limited or supply limited (Bovis & Jakob, 1999), a state that can fluctuate (Bennett et al., 2014). In transport limited mountainous channels underlain by weak material (e.g., glacial till), a surfeit of sediment exists and thus debris flow initiation is controlled by meteoric events (Jakob et al., 2005). However, many mountainous channels are supply-limited. Debris flows rapidly erode channel sediment as deep as 10 m (Anderson et al., 2015; Pierson, 1980; Rickenmann & Zimmermann, 1993) stripping the channels down to bedrock (e.g., Benda, 1990; Stock & Dietrich, 2003, 2006; Wohl & Peartree, 1991), then the bedrock channel refills...
Figure 1. (a) Oblique view of the study channel reach and the full contributing area (38.73148°N, −106.1829°W). The bridge is used to mount instruments such as a laser and rain gage that are used to monitor debris flow processes in the underlying channel. (b) The Chalk Cliffs study site near Mount Princeton in Chaffee County, Colorado, USA. The white cliffs are composed of hydrothermally altered quartz monzonite. (c) Study area location. (d) Closeup view of the sediment fence. Dashed line indicates upslope contributing area (22 m²), and the arrow indicates the direction of sediment movement. Fence is 2.4 m long by 0.4 m tall and was sufficient to capture all sediment generated from upslope.

with sediment from upslope geomorphic processes (Anderson et al., 2015; Bovis & Jakob, 1999; Glade, 2005; Jakob et al., 2005). Consequently, in these supply-limited bedrock channels, the probability of a new debris flow in the same reach is directly linked to the sediment channel refilling rate (Bovis & Jakob, 1999; Coe et al., 2008; Glade, 2005; Jakob et al., 2005; Martin et al., 2017).

Which geomorphic processes set the sediment recharge rate in debris flow prone channels? The rate of channel sedimentation must be set by the rate of bedrock weathering and regolith transport (Jakob et al., 2005), and field observations suggest the rate of channel sediment recharge varies with regionally dominant geomorphic processes (e.g., upstream mass failure, Bennett et al., 2013; Jakob et al., 2005; bedload transport via water-dominated flows that deposit large gravel wedges, Theule et al., 2012; dry ravel, Jackson & Roering, 2009; or solifluction, Glade, 2005).
We use a relatively well-studied debris flow research site, the Chalk Cliffs in west central Colorado, USA (Figure 1) (Coe et al., 2008; Kean et al., 2013; McCoy et al., 2010, 2012, 2013) to study the geomorphic controls on sediment recharge in an alpine debris flow channel. Prior research has suggested that dry ravel and rockfall can refill the debris flow channel, and the presence of available sediment in the channel can make the difference between a debris flow and a flood event (Coe et al., 2008). Here, we will build on those initial observations by quantifying the rate, seasonal timing, and control on sediment production at two different scales: a small plot scale, using a fence, and a larger reach scale using structure-from-motion photogrammetry (SfM).

A primary goal of this study is to document the environmental factors that influence rockfall and thus the recharge of sediment in debris flow channels. We hypothesize that sediment production is driven by frost weathering. This hypothesis is motivated by the fact that in the Chalk Cliffs catchment, the debris flow channels fill up with sediment during cold periods (October–May) (Coe et al., 2008). Debris flows typically occur during the summer months (June-September), and by the end of the summer the arterial channel in the watershed is often scoured to bedrock (Coe et al., 2008) (a seasonal cycle that has been observed in other debris flow channels, Berger et al., 2011; Howard, 1998; Loye et al., 2016; Theule et al., 2012). Therefore, within the seasonal debris flow cycle there is an observed correspondence between sediment refilling and seasonally cold conditions, and previous research has shown the influence of frost weathering on sediment production (e.g., Anderson, 1998; Bennett et al., 2013; Matsuoka, 2019; Matsuoka & Murton, 2008; Riebe et al., 2015; Sanders et al., 2012; Scherler, 2014; Tucker et al., 2011). The 9% volumetric expansion of water to ice can generate rock cracking, but this is generally believed to be rare because of the requirement of full water saturation and rapid freezing from all sides (Matsuoka & Murton, 2008). Prior research has suggested that a more plausible cause of frost cracking is segregation ice (Murton et al., 2006; Taber, 1930; Walder & Hallet, 1985, 1986), which forms when water migrates through rock fractures toward the site of freezing, and ice is generated in distinct (segmented) lenses. Moreover, segregation ice formation favors thawing periods with the largest temperature gradients, when water is available for ice growth and cold temperatures deeper in the rock drive water toward microcracks where segregation ice forms (Hallet et al., 1991). The segregation ice leads to rock fractures, as rocks break apart to accommodate the necessary increases in porosity due to ice expansion (Rempel et al., 2016). Acoustic measurements of frost cracking show the most activity in areas with dense fractures, available melt water, and large temperature gradients (Amitrano et al., 2012). Laboratory experiments have shown that maximum frost cracking occurs in the range of −8 to −3 °C and that multiple cracking events can occur on a timescale of several hours (Hallet et al., 1991), although there may not be a sharp lower bound on this window (Girard et al., 2013; Rempel et al., 2016). Based on this observation, it has been suggested that the amount of time rock spends in the frost-cracking window and the gradient of the temperature with depth can serve as a useful index for the amount of rock damage (Anderson, 1998; Delunel et al., 2010; Hales & Roering, 2007).

To test our hypothesis, we investigated different temperature metrics to evaluate potential controls on sediment production. In particular, we explored the efficacy of four different metrics in describing the relationship between sediment production and temperature: mean air temperature, the depth-integrated frost-cracking intensity, the number of freeze-thaw cycles, and the time in the frost-cracking window. Establishing the temperature metric(s) that best predicts sediment production allows us to achieve a second goal in this study: to develop a simple, conceptual model that describes the mass balance in an alpine debris flow channel. Focusing on a 35-m reach of a debris flow channel, we quantified sediment accumulation using SfM during a single winter season and compared this measurement of the volume of channel fill with an estimate of sediment production derived from a series of temperature, wind, and sediment monitoring measurements. Many debris flow channels around the world are located in rock-dominated cold alpine regions. Therefore, the ability to link the primary sources of sediment production to observable channel refilling rates is a necessary precondition for understanding debris flow likelihood and its sensitivity to environmental conditions.

2. Study Site

The Chalk Cliffs study area (0.3 km²) in Chaffee County, Colorado, USA, is known for frequent debris flows during convective thunderstorms (e.g., typically two or more per annum) (Coe et al., 2008; Kean et al., 2013; McCoy et al., 2010, 2012, 2013) (Figure 1). The study basin is composed of highly erodible bedrock, consisting...
of a hydrothermally altered quartz monzonite with a high fracture density, and the colluvium has a similar grain size distribution to the channel sediment (Coe et al., 2008). In addition, there is little vegetation in the basin, with bedrock exposed in approximately 60% of the catchment (Coe et al., 2008). The regional climate is defined by cold winters with snowfall accumulation and high-intensity convective storms in the summer months (June-September) (U.S. Climate Data, 2019). The mean annual air temperature is 6.8 °C, and the mean annual precipitation is 345 mm (Coe et al., 2008).

In this study, we focus on two portions of the 0.3 km² basin at 2,800-m elevation, where we can accurately measure sediment accumulation: a 35-m reach of bedrock channel (3,200 m² contributing area) (Figures 1a and 1c), and a much smaller 22-m² subbasin, which has a fence at the bottom to collect sediment (Figures 1b and 1d). The 35-m reach of channel has a seasonal cycle of sediment accumulation from the adjacent hillslopes in the winter and sediment export by debris flows in the summer. This reach contains the “Upper Station” where debris flows have been documented previously at this site (Kean et al., 2013; McCoy et al., 2010, 2012, 2013), making the site ideal for exploring how debris flow channels recharge with sediment after they erode to bedrock. The area upstream of the study reach is inaccessible to human foot traffic due to safety concerns (i.e., falling rock).

We primarily observe sediment movement into the study channel and fence via falling rock or dry ravel. During the winter, we do not see evidence of rills or fluvial channels in the study reach that would indicate water transport of sediment from the hillslope, but snowmelt and wind appear to influence sediment movement. Because the channel itself has a much lower slope than the adjacent hillslopes and flow is ephemeral, it generally serves as a depositional portion of the landscape, collecting material from rockfall and dry ravel. Moreover, negligible material moves into or out of the study channel reach via water flow processes during the winter months; the material in the channel reach is only mobilized during convective thunderstorms.

3. Methods

3.1. Temperature and Wind Observations

We set up a temperature measurement system modeled after Anderson (1998) to observe temperature fluctuations over time and as a function of depth (Kean et al., 2019). Rock temperature was measured as a function of depth using custom-built thermistors placed beside the sediment fence at the following depths: 0, 1, 2, 4, 8, 16, 24, 32, and 42 cm. The thermistors were inserted into holes drilled into the rock and filled with a mixture of epoxy and rock flour to ensure good thermal coupling to the rock. One instrument was placed on a south facing exposure near the sediment fence and a second instrument was placed on a north facing exposure across the channel (Figure S1 in the supporting information). Here, we will focus on the instrument on the south facing side near the sediment fence. Temperature measurements were obtained at a time interval of 1 min for portions of the years 2011, 2012, 2013, and 2015. The entire year of 2014 had continuous measurements, whereas there were data gaps in the other years during maintenance periods. Detailed temperature observations provide high temporal resolution of heat transfer into the rock mass making up the cliff walls at the study site. In addition, we explored the role of wind using a MetOne 034b anemometer that monitored wind speed.

3.2. Plot-Scale Sediment Accumulation

To correlate measurements of temperature with sediment production, we made plot-scale measurements by installing a solid fence to capture all the material from a steep 22-m² plot (Figure 1d). The average slope angle of the area upstream of the sediment fence is 44.1°. There is minor sediment retention on portions of the slope <44°. Coincidentally, tilt-table experiments suggest that the internal angle of friction for sediment at the site is 44° ± 1° (McCoy et al., 2012).

Sediment accumulation behind the fence was recorded between 2011 and 2017 near the beginning and end of each debris flow season (every 197 days on average), and these data provide a multiyear record of sediment production from a bare-bedrock area. Periodically (usually at the beginning/end of a season), the fence was cleaned of all debris with a negligible amount of weathered material remaining on the slope above. The sediment was weighed to convert to a volume using a bulk density (1,670 ± 150 kg m⁻³) based on three different measurements taken from the sediment fence.

To more precisely observe the timing of sediment accumulation and its association with water availability and wind speed, we installed a time lapse camera that took pictures of the fence three times a day between November 2011 and April 2014. A 2-cm grid outline on the white fence face was used to quantify the depth of sediment on the face with time. We used photogrammetry to develop a relation between the height
of sediment along the fence face and the volume of stored material (Movie S1). Although photo-derived estimates of sediment volume were made at a much higher frequency than the measurements from weighing sediment (3 times a day versus an average of every 197 days), the photo estimates are subject to much greater uncertainty than the weight-based volume measurements. This uncertainty is primarily due to unknown variations in deposit density, which could vary greatly, especially when sediment was mixed with snow. We use the photo-derived estimates of sediment volume to track the timing of sediment delivery in relation to temperature and wind speed measurements.

### 3.3. Reach-Scale Sediment Accumulation

To measure sediment production at a larger scale than the 22-m² fence plot, we used repeat Structure-from-Motion surveys to quantify sediment accumulation in a 35-m channel reach with a contributing area of 3,200 m². Two surveys were conducted ∼9 months apart on 15 September 2015 and 1 June 2016 (Figure 2) to quantify the volume of accumulated sediment during that time period (Rengers & Reitman, 2019). In preparation for the first survey, the channel bottom was swept clean to expose bare bedrock and 25 bolts were drilled into the sides and bottom of the channel for control points. The control points were surveyed in a local coordinate system using a total station. Both photogrammetric surveys were conducted with a Nikon AW1 mirrorless camera, using autofocus and various zoom levels. The first survey resulted in 1,187 photos taken over a period of ∼2 hr. The second survey resulted in 1,085 photos taken in a similar time span. The second survey was conducted prior to the onset of debris flow activity for the 2016 summer season.

Point clouds and surface models were constructed from each photoset using Agisoft Photoscan Professional software version 1.2.6 build 2834. The Nikon AW1 camera was calibrated for each zoom level, and the results of lens calibration were used during model construction. CloudCompare software was used to downsample the SfM point clouds to an average of 1 pt/cm².

Each SfM point cloud was interpolated to a triangular irregular network (TIN) and subsequently to a digital elevation model (DEM) with a 0.01-m pixel size using ArcGIS 10.2. Using the resulting DEMs from each survey, we calculated the change in elevation for each DEM pixel using

\[ Z_{\text{diff}} = Z_{i2} - Z_{i1} \]  

where, \( Z_i \) is the elevation of each pixel, and the subscripts 1 and 2 represent the first and second survey epochs, respectively. The measurement uncertainty (\( U \)) was taken into account using the point cloud registration uncertainty from Agisoft (\( U = 0.022 \) m). The minimum level of detection was set equal to the total uncertainty \( U \) (Brasington et al., 2000; Wheaton, 2008); therefore, pixels with a change in elevation between \( \pm U \) were masked out of the difference analysis.

### 3.4. Temperature Analysis

In order to understand how temperature influences sedimentation, we compared air and rock temperature measurements at depth with the sedimentation rate behind the sediment fence (Figure 1d). Prior work has suggested that frost-cracking intensity is related to the time spent in the frost-cracking window.
Table 1

| Start date | End date   | Days of measurement | Sediment mass (kg) |
|------------|------------|---------------------|-------------------|
| 21 Nov 2011| 12 Mar 2012| 112                 | 294.4             |
| 12 Mar 2012| 6 Nov 2012 | 239                 | 107.3             |
| 6 Nov 2012 | 19 Jun 2013| 225                 | 417.7             |
| 19 Jun 2013| 15 Nov 2013| 149                 | 84.6              |
| 15 Nov 2013| 9 Apr 2014 | 145                 | 389.2             |
| 9 Apr 2014 | 9 Dec 2014 | 244                 | 222.9             |
| 9 Dec 2014 | 28 May 2015| 170                 | 296.1             |
| 28 May 2015| 8 Oct 2015 | 133                 | 112.5             |
| 8 Oct 2015 | 1 Jun 2016 | 237                 | 400.8             |
| 1 Jun 2016 | 7 Sep 2017 | 463                 | 470.2             |

(Anderson, 1998). Hales and Roering (2007) used the temperature gradient of the subsurface within the frost-cracking window (\(-8 \leq T \leq -3\)) (Hallet et al., 1991) as a proxy for the intensity of frost cracking. Delunel et al. (2010) named this metric the depth-integrated frost-cracking intensity (DFCI). Hales and Roering (2007) used the annual sum of the DFCI to quantify the rate of segregation ice growth during a year. Here, we employ a modified version of this statistic where we sum the temperature gradient within the frost-cracking window during the time period between measurements of sediment production at the sediment fence (rather than for an entire year), using the following approach:

\[
DFCI = \begin{cases} 
\frac{1}{Z_n} \sum_{i=1}^{n-1} [T(Z_{i+1}) - T(Z_i)], & -8 \leq T \leq -3; \\
0, & \text{otherwise}
\end{cases}
\]  

(2)

\[
F = \frac{1}{t_s - t_0} \sum_{j=t_0}^{t_s} DFCI_j
\]  

(3)

where \(n\) is the total number of depths at which temperature was measured, \(i\) indicates the index of the depth of each thermistor, \(Z\) represents the depth, \(Z_n\) represents the length where temperatures are in the frost-cracking window, \(T\) is the temperature, \(F\) is the sum of the DFCI between the sedimentation periods, \(j\) is the index of each time step (in this case we use a 1-min interval), \(t_0\) is the starting time of fence sedimentation recording, and \(t_s\) is the final time of fence sedimentation recording. Finally, we assume that when \(F\) is high, there is sufficient moisture to allow for segregation ice formation. In addition, we calculate the number of times that temperatures crossed the freeze-thaw boundary (FTB) to see if the number of freeze-thaw cycles are an important driver of sediment production (e.g., Bennett et al., 2013).

In order to better differentiate the type of frost-weathering process that may be influencing sediment production, we compared the sedimentation rate \([\text{kg} \cdot \text{m}^{-2} \cdot \text{day}^{-1}]\) versus air temperature, \(F\), \(FTB\), and the amount of time spent in the frost-cracking window \((W)\). Because the duration of each sedimentation record is different (Table 1), we normalized the sediment data by time. Unfortunately, there were several points where sedimentation was measured, but the temperature was not measured due to data logger maintenance. During those periods, we were able to fill in some of the data gaps for the comparison of sediment production versus air temperature. In these cases, we used a weighted average of the mean monthly temperature for each day in the sedimentation period. For example, if the sedimentation measurement was conducted for 10 days in October and 30 days in November, we would multiply 10 by the mean monthly temperature for October and 30 by the mean monthly temperature of November, and then calculate the average of those temperatures. We did not estimate \(F\), \(FTB\), or \(W\) if data were unavailable, because we have lower confidence that the averages of those measurements are reliable proxies.

4. Results

4.1. Visual Observations of Sedimentation

Time lapse photos showed that the largest pulses of sediment delivered to the fence were associated with winter snowstorms (Figure 3 and Movie S1 in the supporting information). Daytime sunshine after the
storms often quickly melted the snow and supplied moisture needed for frost cracking, although frost cracking from segregation ice is thought to move via thin water films (Walder & Hallet, 1985) and may not require large water inputs. Near-surface rock temperatures during the snowstorm and snowmelt periods were typically in the frost-cracking window for many hours each 24-hr period (Movie S1).

We observed little sediment accumulation during times when the near-surface rock temperature (≤15 cm) was not in the frost-cracking window (Movie S1). Although most large temperature drops were associated with some snowfall, there were some days when the temperature was in the frost-cracking window and it had not snowed recently. During these times, we observed little sediment accumulation behind the fence. This may suggest that the moisture from snow is important for destabilizing loose material and promoting particle movement. During an entire winter of video monitoring, we observed sediment transport via individual particle movement, and granular creep, but we did not observe sediment entrained in overland flow from snowmelt or snowmelt-induced mass failure (Movie S1).

Wind also played a role in transporting sediment to the fence. Small pulses of sediment to the fence were associated with wind gusts, which often exceeded 10 m/s (Movie S1). Presumably some of the sediment that was produced on the 44° slope above the fence (which is coincidentally equal to the sediment friction angle) was initially unstable and later mobilized by wind. We assume that the wind was important in nudging gravitationally unstable sediment that had been detached from frost weathering but that it was not a primary driver of rock erosion.

4.2. Sediment Accumulation and Temperature at the Plot Scale

Temperature measurements show the temperature variability at the site as well as the time spent in the frost-cracking window. The mean annual rock surface temperature is 6.4 °C (Figure 4). However, there is a high diurnal variability in the rock surface temperature, where temperature
swings of 15 °C are not uncommon (Figures 5 and 6). A snapshot of the measured temperature variability for an entire year as a function of depth (Figure 6) shows shifts in temperature over time that correspond well with temperature models (e.g., Anderson, 1998).

To determine how segregation ice may be forming with depth, we used available temperature data from 2014, which was the only year without data gaps. During 2014, we found that the rock surface entered the frost-cracking window on 78 days (Figure 7a). That time decreased to 30 days at 16 cm below the surface.
Figure 7. (a) The number of days in 2014 spent in the frost-cracking window (−8 to −3 °C) at depth. The legend denotes each month (numbered) and the corresponding colors. Results here are displayed for 2014, which had complete monthly data. The gray box represents the frost-cracking window between −8 and −3 °C.

(Figure 7a). The minimum temperature value each month shows that the top 32 cm of rock are capable of attaining temperatures in the frost-cracking window (between −8 and −3 °C) for seven months of the year (Figure 7b). We used the minimum temperature because the mean temperatures can be substantially higher than the lowest daily temperatures (Figures 5a and 5b), and would therefore underestimate the depth at which temperatures are capable of reaching the frost-cracking window.

When sediment fence measurements (Table 1) were compared with the mean air temperature during the period of measurement, we found that the most sedimentation occurs during cold periods and less sedimentation occurs during warm periods (Figure 8a). The sediment production is also shown to be strongly related

Figure 8. Comparison of the measured fence sedimentation rate versus (a) the mean air temperature during the same period. Gray triangles represent data points where the air temperature was not measured and therefore was estimated using a weighted average of mean monthly temperature. Note that the gray triangles are used for the linear “best fit” equation. (b) The sum of the DFCI between sediment measurement periods at the sediment fence. (c) The number of times the rock surface temperature crossed 0 °C. (d) The time the rock surface spent in the frost-cracking window. Note that the length of time for each sedimentation record is shown in Table 1.
4.3. Sediment Accumulation at the Reach Scale

At the reach scale, the SfM survey captured the volume of sediment deposited in the channel during a single winter refilling period. The DEM of difference (DoD) created from the SfM surveys records an increase in sediment volume in the channel reach of $V_c = 18.1 \text{ m}^3 \pm 0.6 \text{ m}^3$, where the uncertainty represents the area within the level of detection (e.g., $Z_{\text{diff}} < 0.022 \text{ m}$) (Figure 9). This volume is attained by multiplying the change in elevation of each pixel $Z_{\text{diff}}$ by the pixel area $0.0001 \text{ m}^2$ and summing all pixels, with the exception of areas $< |0.022|$. The DoD shows that the distribution of sediment deposition is spatially variable, with the majority of sediment collecting in preexisting bedrock potholes (Figure 9a).

4.4. Extrapolating Sediment Production

Our measurements of sediment production, air temperature, $F$, $FTB$, and $W_t$ offer predictive relationships that can be used to generate estimates of sediment production at larger scales (Figure 8). We can evaluate these predictions by comparing a predicted volume of sediment production at the reach scale versus the observed sedimentation volume from the DoD. During the SfM measurement period, the temperature sensors at our site were removed (preventing us from using $F$, $FTB$, or $W_t$ for sediment production estimates). However, we used air temperature data from the closest nearby temperature sensor and adjusted the air temperatures for our site using the calibrated relationship between temperature measurements from the two

Figure 9. Sediment change in the channel during the survey period. (a) DEM of the difference between the first and second surveys. Areas below the level of detection are masked out in black. Gray dashed line shows the location of a longitudinal profile from $X$ to $X'$. (b) Longitudinal profile showing channel bottom topography during each survey and depositional change between the surveys.
Figure 10. Oblique view and slope of the study area. The contributing area to the study channel is indicated with a dashed line. The solid line indicates the path used for modeling dry ravel (see supporting information). The color bar shows the slope, and the areas equal to the friction angle (44°) are shown in white. Flow direction is indicated by an arrow. Scale bar in meters, located in the lower right. The inset shows the real-color point cloud in 3-D.

sites based on, 1.5 years of recorded data (Figure S2). We used the regression equation of sediment production from air temperature (Figure 8a) to predict the actual sediment generated in the study basin (3,200 m²). Using the calibrated daily temperatures during our SfM survey period, we estimated a sediment volume using the bulk density, which gives a range of 23.8–41.5 m³. We also performed a limited model analysis (see Figure S3) to consider the likelihood that sediment eroded from the steep cliff walls surrounding the channel would move into the channel with minimal intermediate storage using the steepest transect between the cliff and the channel (Figures 10 and S3). Those model results suggest limited hillslope storage, which agrees with field observations of minor sediment retention on the slopes adjacent to the channel (Figure 1).

5. Discussion

5.1. The Importance of Frost Weathering for Sediment Production in Debris Flow Channels

Prior work has described a feedback cycle between channel filling, debris flows, and channel reloading (Anderson et al., 2015; Bennett et al., 2013, 2014; Bovis & Jakob, 1999; Glade, 2005; Jakob et al., 2005). This work expands on the work of Hales and Roering (2007) who link rockfall to elevation zones in mountainous regions with high frost-cracking intensity, by quantifying the sediment production rate of periglacial processes (Figure 8). Sediment production ultimately sets the sediment recharge in debris flow channels, thus controlling debris flow frequency. Our observations show a strong link between sedimentation and temperature using several years of data collection (Figure 8), which implicates frost weathering as a likely driver of sediment production, supporting prior suggestions of this linkage (Bennett et al., 2013). In particular, the robust relationship between sediment production and air temperature, \( F \), and \( W_t \), lends support toward segregation ice as the particular driver of frost weathering. Moreover, the relatively weak relationship between sediment production and the number of times that the freeze-thaw boundary is crossed (Figure 8c) also suggest that freeze-thaw cycles are not the primary driver of frost weathering.

5.2. Implications for Debris Flows

The processes observed in this study have implications for explaining debris flow reloading patterns in steep alpine landscapes with abundant exposed bedrock. The predicted sediment production for the catchment using the linear regression from Figure 8a during the period of the SfM survey suggests a volume of material between 23.8 and 41.5 m³ (the range reflects uncertainty in the bulk-density measurements) that would likely move into the channel, which is on the same magnitude as the SfM measured volume of 18.1 m³ in the channel. It is likely that a small fraction of the sediment remained on portions of the slope less than the angle of friction, which would further increase the similarity between the measured and predicted volumes of sediment. There may be other factors that could also explain the differences in these volume estimates.
including moisture differences in different parts of the study basin that influence frost-weathering or differences in temperature with respect to hillslope aspect. We do not have sufficient data to document moisture differences throughout the study basin to quantify the influence of this factor; however, we compared the rock surface temperature from the probes near our sediment fence to probes placed on an opposing north facing hillslope aspect. We found that the mean rock surface temperature on the opposing hillslope aspects during each period of sediment production measurements were similar (Figure S1). In fact, the rock surface temperature on the two opposing aspects show an $R^2$ value of 0.995 when they are regressed, revealing a similarity in the mean surface temperatures on opposing hillslope aspects. Despite the uncertainties, the similar volume magnitudes between the SfM observations and air temperature sedimentation predictions show that calibrating and estimating sediment production in other cold high alpine debris flow catchments could be a step toward better quantifying debris flow frequency.

Consequently, this data set allows us to link the source of sediment production (frost weathering) directly to channel refilling. The clear correlation between temperature and sedimentation shows that rockfall refilling is not random; rather, it is associated with cold temperatures. Moreover, the sediment in the channel does not form conical piles (e.g., Florsheim et al., 2016), but sediment fills up the low points (potholes) preferentially (Figures 2 and 9), which are the most likely locations to stop sediment moving off the steep slopes at high velocities (Figure S3). These observations also open an opportunity to determine the likelihood of debris flow initiation in future work, by pairing a frost-weathering sediment production rate with the minimum bed material depth required for debris flow initiation.

More generally, this study suggests a continuum of sediment filling and debris flow transport that will influence both landscape evolution (e.g., Anderson et al., 2013) and debris flow hazards in steep bedrock catchments. In mountain regions like our study area, we suggest that there is a seasonal competition between winter/spring channel filling from rock weathering and debris flows during the summer, as also found in the Swiss Alps (Bennett et al., 2013; Berger et al., 2011). The specific geomorphic transport processes can be partitioned into three groups: sediment production from bedrock weathering, sediment transport into a channel via rockfall, and debris flow transport during the warm season (Figure 11). In this type of landscape, the channel has a low slope relative to the surrounding hillslopes and therefore can act as a reservoir to retain sediment until debris flow transport (as previously observed in the Illgraben Catchment (Bennett et al., 2014)).

A mass balance approach can be used to quantify the state of channel refilling or erosion for a debris flow prone watershed:

$$\frac{dM}{dt} = \mu_{in} - \mu_{out}$$ \hspace{1cm} (4)

where the change in mass $M$ per time $t$ is balanced by the mass flux in $\mu_{in}$ ($MT^{-1}$) and out $\mu_{out}$ ($MT^{-1}$). If we consider the outflow of material at the basin outlet, the mass balance can be expressed as

$$\frac{dM}{dt} = \rho_s S A_B - \rho_s V_D \zeta$$ \hspace{1cm} (5)

where $\rho_s$ is the measured bulk density of sediment, $S$ is the rate of sediment production ($LT^{-1}$), $A_B$ is the total basin area that contributes sediment, $V_D$ ($L^3$) is the total volume exported past the basin outlet during a debris flow, and $\zeta$ ($T^{-1}$) is the annual frequency of debris flows. In addition to cold alpine catchments where sedimentation processes could be quantified based on temperature relationships, this general expression could be adapted to estimate the sediment balance in burned steeplands where dry ravel sedimentation rates
can be estimated (e.g., DiBiase & Lamb, 2013; Lamb et al., 2011), the frequency of wildfires and triggering rainstorms could be used to estimate debris flow frequency, and total debris flow volumes could be estimated from empirical relationships (Gartner et al., 2014). Finally, a rainfall threshold or a debris flow initiation model could be used to estimate the annual export of debris flow material (e.g., Bennett et al., 2014).

Using this natural experiment, we are able to show when, from where, and how sediment refills channels between debris flows. Given the competing processes of channel sedimentation and debris flow erosion linked to temperature, it is possible to imagine how the landscape would change as the climate fluctuates over time. For example, if sediment production continued, but summer thunderstorms weakened, thus reducing debris flow activity, channel filling would occur over time and channel bed erosion would decrease. Climate records suggest that in the past, the North American Monsoon weakened during periods of glaciation and strengthened during warmer interstadial periods (e.g., Wagner et al., 2010). During the late Holocene, periods of extended cold were contemporaneous with megadroughts, and warm periods increased the strength of the North American monsoon (Barron et al., 2010; Miller et al., 2010; Asmerom et al., 2013). Moreover, during the Last Glacial Maximum, the presence of the Laurentide ice sheet disrupted the development of the North American Monsoon west of the Continental Divide (Adams & Comrie, 1997), which would have reduced summer thunderstorm activity at our study site. Warmer sea surface temperatures in the eastern tropical North Pacific helped to strengthen the North American Monsoon beginning in the early Holocene (Liu et al., 2003). Consequently, this helps to explain large sediment packages along the mountain front observed near our study site (see Figure 2b in McCoy et al., 2012); the sediment packages could have formed when cold temperatures produced abundant sediment, but storms were insufficient to move the sediment downstream. The current conditions of the site are allowing annual debris flows to excavate these large sediment packages. Alternatively, if an increase in overall temperature occurred such that periglacial processes no longer acted on the landscape, this would change the sediment production rates. The sediment production would likely decrease, reducing the sediment load available for debris flows, potentially reducing the debris flow hazard. Equations (4) and 5 provide a framework for exploring those scenarios. These scenarios are speculative, but reflect the growing body of work that shows the link between climate conditions and mass wasting (Coe et al., 2018; Gruber et al., 2004; Micheletti et al., 2015; Stoffel & Huggel, 2012).

Finally, these results have broader implications, beyond debris flows, for assessing rockfall and weathering rates. For example, it may be possible to define a temperature threshold where rockfall activity would increase (e.g., Gunzburger et al., 2005), or to assess the potential summer debris flow threat by tracking the winter temperature and estimating the debris flow channel sediment refilling rate. This should be combined with further research into the frost-cracking window, as there is an existing debate on the exact temperature window bounds (McGreevy & Whalley, 1982), and emerging evidence that a lower temperature bound may not exist (Girard et al., 2013; Rempel et al., 2016).

6. Conclusion

In vertiginous landscapes where debris flows occur frequently, one chief constraint on debris flow initiation is the sediment recharge rate between events. In this study, we identified the dominant process involved in sediment production from bedrock in an alpine basin and showed how sediment production in bedrock areas is linked to sediment accumulation in the debris flow channel. Temperature data from the field site suggests that rock temperatures are cold enough for frost weathering for at least 7 months year\(^{-1}\). We also see a strong correlation between sediment production and mean air temperature, depth-integrated frost-cracking intensity, and the time in the frost-cracking window. A weak relationship was observed between sediment production and the number of freeze-thaw cycles. We used air temperature to predict sediment production into a bedrock-channel reach, and the predicted sediment production matched closely with the sediment accumulation measured from SfM surveys of the debris flow channel. Spatial analyses helped to confirm that the majority of sediment entering the channel results from sediment production on bedrock slopes. From these site investigations, we suggest a mass balance modeling approach that could be used as a guide to estimate whether a debris flow producing watershed is refilling or being exhumed. Using the observations of sediment production as a function of temperature metrics, it should be possible to hindcast the sediment supply during cooler climate scenarios, to forecast how sediment supply to debris flow channels will change in warmer climate scenarios, or to explore how the balance between sediment production and debris flows change with increased variability in precipitation and temperature.
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