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OBSERVATIONS OF DEBRIS FLOWS AT CHALK CLIFFS, COLORADO, USA: PART 2, CHANGES IN SURFACE MORPHOMETRY FROM TERRESTRIAL LASER SCANNING IN THE SUMMER OF 2009

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ABSTRACT

High resolution topographic data that quantify changes in channel form caused by sequential debris flows in natural channels are rare at the reach scale. Terrestrial laser scanning (TLS) techniques are utilized to capture morphological changes brought about by a high-frequency of debris-flow events at Chalk Cliffs, Colorado. The purpose of this paper is to compare and contrast the topographic response of a natural channel to the documented debris-flow events. TLS survey data allowed for the generation of high-resolution (2-cm) digital terrain models (DTM) of the channel. A robust network of twelve permanent control points permitted repeat scanning sessions that provided multiple DTM to evaluate fine-scale topographic change associated with three debris-flow events. Difference surfaces from the DTM permit the interpretations of spatial variations in channel morphometry and net volume of material deposited and eroded within and between a series of channel reaches. Each channel reach experienced erosion, deposition, and both net volumetric gains and losses were measured. Analysis of potential relationships between erosion and deposition magnitudes yielded no strong correlations with measures of channel-reach morphometry, suggesting that channel reach-specific predictions of potential erosion or deposition locations or rates cannot be adequately derived from statistical analyses of pre-event channel-reach morphometry.

***Key words**: debris flow, terrestrial laser scanning, morphometry, channel*

INTRODUCTION

Runoff-generated debris flows are common in sparsely vegetated or recently burned steeplands throughout the world (Berti *et alii*, 1999; Cannon *et alii*, 2001a; Cannon *et alii*, 2001b; Cannon *et alii*, 2003; Godt & Coe, 2007; McArdell *et alii*, 2007; Coe *et alii*, 2008; Santi *et alii*, 2008). Relative to flows that mobilize from a discrete landslide source, the mechanisms that contribute to the initiation and propagation of debris flows produced during runoff events are less understood (Cannon *et alii*, 20003; Berti & Simoni, 2005; Coe *et alii*, 2008; McCoy *et alii*, 2010). Runoff-generated debris flow occurs in response to surface flow produced during a rainstorm. Overland flow initiates as rainfall intensity exceeds infiltration capacity. Surface runoff then entrains material from the hillslopes forming rills and gullies (Gabet, 2003; Moody & Kinner, 2006; Shakesby & Doerr, 2006; Gabet & Bookter, 2007). Although hillslopes provide an important source of material, it has been recognized that a significant portion of the debris-flow volume is generated by erosion of channel fill (Cenderelli & Kite, 1998; Bovis & Jakob, 1999; Jakob *et alii*, 2005; Santi *et alii*, 2008). Mobilization of material stored in the channel can be considered to be the product of shear forces applied on the bed by the flow, impulsive loading, liquefaction of channel fill, bank

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failure, and headward migration of knickpoints (Bovis & Dagg, 1992; Egashira *et alii*, 2001; Hungr *et alii*, 2005). Channel deposition will occur when friction increases along flow margins and internal pore-fluid pressures diminish (Major, 2000).

While there is a growing body of work on debris-flow entrainment from single events, there has been little research regarding the spatial patterns of both channel erosion and deposition from multiple events. Data related to channel erosion, deposition and volumetric growth of debris flows has traditionally been collected from cross-sections (Chen *et alii*, 2005; Santi *et alii*, 2008), photogrammetry (Coe *et alii*, 1997; Cenderelli & Kite, 1998; Veyrat-Charvillon & Mernier, 2006), and more recently with airborne LiDAR (Scheidl et al., 2008) and terrestrial laser scanning (TLS) data (Wasklewicz & Hattanji, 2009). Many of these studies do not consider data regarding pre-event channel morphometry because a low debris-flow frequency in most locations does not allow for the collection of pre- and post- event channel morphometry data. Therefore, these studies rely upon assumptions of the channel shape prior to the debris flow that limit the broader applicability of the results. These studies have been further limited by their examination of a single event, which likely is not representative of the long-term debris flow record where multiple debris flow events are interacting to produce channel changes.

The Chalk Cliffs study basin near Buena Vista, Colorado presents a unique opportunity to study the patterns of channel erosion and deposition, and the volumetric changes from multiple debris flows. The Chalk Cliffs have one of the highest debris-flow frequencies in Colorado, where 1-4 debris flows are typically recorded each summer (Coe *et alii*, 2008; McCoy *et alii*, 2010). Here, we present results from four TLS surveys at Chalk Cliffs: the first was on 28 May 2009 and documented the channel configuration prior to the onset of the summer debris flow season; three additional surveys conducted during the summer documented changes in channel form associated with individual debris-flow events.

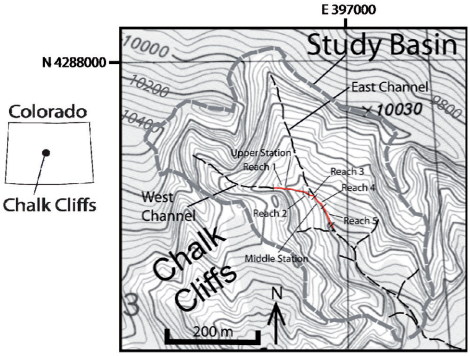

Fig. 1 - Chalk Cliffs study area. Contour interval is 40 m

The purpose of this paper is to document the topographic changes that occurred in the stream channel as a response to each debris-flow event. We compare and contrast the morphologic response of the channel by calculating 1) the net volume of material eroded from the channel, 2) the net volume of material deposited in the channel, and 3) the net overall volumetric change that occurred in the channel reach. In addition, we analyze the changes in mean channel-reach gradient and surface roughness associated with each debris-flow event, and attempt to predict net volumetric change as a function of reach-scale morphometry.

STUDY AREA

The Chalk Cliffs study basin (Fig. 1) is a 0.3 km^2 watershed composed of a hydrothermally altered quartz-monzonite (Miller *et alii*, 1999). Primary geomorphic units in the basin include exposed bedrock and sandy colluvium. Bedrock is exposed in approximately 60 percent of the basin, with gradients ranging from approximately 80 percent to vertical. The sandy colluvium occupies the remaining 40 percent of the watershed, with gradients ranging between 50 and 100 percent (Coe *et alii*, 2008). Frequent rockfall and dry-ravel processes contribute material to the channel. Debris flows initiate in both the east and west channels (Fig. 1) in response to bursts of high intensity rainfall typically associated with short-duration convective rainstorms (Coe *et alii*, 2008). These storms have produced debris flows of varying magnitudes, with some flows terminating a short distance from the confluence of the east and west channels (McCoy *et alii*, 2010), and others traveling the entire 0.6- km length of the channel and depositing as a fan at the confluence with Chalk Creek (Coe *et alii*, 2008).

Here, we analyze a non-vegetated portion of the channel beginning just below the lowermost cliff band in the west basin (red line in Fig. 1). We divided the 149 m surveyed length of the channel into five separate reaches based on morphology (Fig. 1). Reach 1 is 27 m long, and occupies the lowermost portion of the west channel. This reach is relatively steep (approximately 30 percent), and consists primarily of exposed bedrock. What channel fill is there consists of debris-flow deposits and colluvium that accumulates between debris-flow events. Reach 2 occupies the lowermost portion of the west channel. This is the shortest (8.5 m) and steepest reach (55 percent gradient), and is best characterized as a bedrock step. Colluvium fills in the shallower-gradient portions of the reach between debris-flow events. Reach 3 occurs at the confluence of the east and west channels. The bed material consists primarily of debris-flow deposits. This 12-m-long section of channel has the lowest mean gradient of all the analyzed reaches (roughly 22 percent). Reach 4 occupies the main channel below a small (roughly 2 m high) boulder step. This 52 m length of channel is typically filled with debris-flow deposits and colluvium, and no bedrock was exposed in the upper two-thirds of the reach during the summer of 2009. Debris flows periodically scour the channel to bedrock in the lower third of the reach. The average gradient for Reach 4 is approximately 30 percent. Reach 5 is the second longest (49 m) and has the second shallowest gradient (roughly 28 percent) of the analyzed reaches. The bed consists of debris-flow deposits and colluvium, with no exposed bedrock. Reach 5 is unique in that nearly the entire west bank consists of a scree slope at the angle of repose, which provides a continuous supply of material to the channel.

METHODS

Assessment of the magnitudes and locations of erosion and deposition associated with each debris-flow event relied upon repeat TLS surveys and geographic information systems (GIS) analysis of the survey data. TLS surveys conducted with a Leica Geosystems ScanStation 2. Accurate depiction of fine-scale (<1 cm) changes in surface elevation between the surveys required a robust control network and the reduction of data voids associated with surface shadowing from topographic roughness elements (e.g. steep slopes, overhangs, boulders). To accomplish this, twelve control points were established in the study basin, consisting of either an expansion bolt drilled into bedrock, or a single 50-cm length of rebar driven into the ground and cemented in place. Leica Geosystems High Definition Survey (HDS) targets were set up on each monument. This network of control points served two purposes: first, they allowed for the registration of scans from multiple instrument set-ups with high accuracy and precision (to remove void spaces resulting from shadowing); and second, they allowed for the use of a common Cartesian coordinate system between each of the four surveys. For each survey, scans were recorded at 13 different locations within the study reaches, producing a point cloud with average point spacing in excess of 6000 points/m^2.

Leica Geosystems CYCLONE and ESRI ArcGIS programs were used to post-process the data, and produce and analyze 2-cm digital elevation models (DEMs) of pre- and post-event topography. A 25-cm DEM was also generated. Post-processing was minimal, as each point cloud was already "bare-earth" given a complete lack of vegetation in the analyzed channel. Anomalous points, such as dust particles, were manually removed. The post-processed TLS data were then brought into ArcGIS to generate DEMs and analyze topographic change. A triangulated irregular network (TIN) was created from the raw point cloud and used to produce the DEMs. Topographic changes between sequential scans were calculated by subtracting the DEM of the post-event surface from that of the pre-event DEM surface. Positive values indicated areas of deposition, while negative values indicated areas of erosion. Volumetric change, V (m^3) was calculated for each cell and totaled for the analysis area, A (m^2) as follows:

$$V = A * \sum_{i=1}^{N} \Delta Zi \qquad (1)$$

where ΔZ_i = change in elevation at the pixel (m).

The morphometric parameters, gradient and roughness, were calculated from the 2-cm DEMs in ArcGIS. Gradient was calculated at the scale of the channel reach as the mean of all 2-cm pixels located along the channel centerline. Roughness was calculated at both particle and channel form scales. Roughness was calculated as the standard deviation of gradient within a 5x5 pixel neighborhood (Frankel & Dolan, 2007). We used the 2-cm resolution DEM to quantify roughness at the particle scale, and the 25-cm resolution DEM to quantify roughness associated

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with channel form. The mean of each reach was then calculated for both measures of roughness.

We assessed systematic errors, root mean square error, and error propagation (Tab. 1) using errors associated with the registration data from the 187 control points common between individual scans and surveys. Systematic error, SE was calculated to detect any trends in the surveying and registration processes:

$$SE = \frac{\sum_{i=1}^{n} \Delta Z_t}{n} \tag{2}$$

where n = number of control points and ΔZ_t = elevation error at control point (m).

SE revealed virtually no bias in any of the four surveys (Tab. 1). Given the independent, randomly distributed target errors, and lack of systematic errors, root mean square error (RMSE) values were calculated to obtain a global error for each survey:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} \left(\Delta Z_t\right)^2}{n}} \tag{3}$$

During volume calculations, RMSE for each included survey had to also be propogated to account for errors in each included survey. For example, the difference surface calculated after the 02 June event included the errors associated with the pre-event surface and the post-02 June surface. Following the law of error propogation for independent, random errors (Taylor, 1982), we use the equation to calculate volumetric error, Ev (m3):

$$E_v = (\sqrt{(RMSE_{i=1})^2 + (RMSE_{s=i+1})^2}) * A \tag{4}$$

where E_v = volumetric error (m^3) and A = analysis area (m^2). Volumetric error was calculated on a reach-by-reach basis for net volumetric change. For cells characterized as either erosion or deposition, the total area of each 0.004 m cell was summed to determine the area of the individual sediment transport processes (either erosion or deposition) per channel reach and that area was used in the calculation of volumetric error. For example, Reach 1 has a total area of 111.79 m2. This value was used to calculate volumetric error for the net sediment yield from the reach. The survey following the 02 June event identified an area of 46.45 m^2 that experienced erosion. This value was used for A (equation 4) in the calculation of volumetric error for eroded material in reach 1 during the 02 June event. For all events, volumetric errors are recorded as ± values (in m) in Table 2. For easier reading, these values are not included in the text. As there is a very small amount of systematic error in any of the surveys, errors in volume likely cancel each other out. As such, the calculated errors represent a "worst-case scenario", and are likely much smaller than those reported.

The quantitative data presented here requires two caveats. First, we have attempted to repeat the TLS surveys as soon as possible after each debris-flow event. In some cases, this represents a period of less than 36 hours (e.g., the 02 June 2009 debris flow). In other cases, several days had passed before the repeat survey could be conducted. During this time, sediment transported from rockfall and dry-ravel processes, and not necessarily debris flow, may have increased the amount of material in the channel. A moderate debris flow that occurred on 06 September 2009 was not recorded and the results of the 29 September 2009 survey reflect the influence of two debris-flow events.

The second caveat is that the measurements of topographic change do not, by themselves fully describe how the deposits were formed. For example, during depositional events (e.g. 02 June 2009), monitoring station data (see McCoy *et alii*, this volume) measured more debris-flow surges than could be identified in post-event topography because multiple surges deposited materials on top of each other. In addition, within single events, water-rich tails eroded material initially deposited by the coarse-grained, fluid-poor surge fronts. Given these two caveats, our measurements represent an erosion minima and depositional maxima associated with the debris-flow events. Even with these limitations, the data presented here represent the documentation of debris-flow changes in channel morphometry in a natural mountain stream channel at an unprecedented spatial and temporal resolution, accuracy and spatial extent.

RESULTS

Four TLS surveys were conducted during the 2009 debris-flow season at the Chalk Cliffs study basin. Here, we present measurements of sediment transport,

Event	Scan Date	# Scans	Systematic Error (mm)	Propogated Systematic Error (mm)	RMSE (mm)	Propogated RMSE for Volume (mm)
Pre-Event Survey	28 May - 01 June 2009	17	-0.10	-0.10	2.24	-
02 June 2009	03 June 2009	11	0.06	0.12	2.98	3.73
26 July 2009	03 - 04 August 2009	10	-0.17	0.24	2.20	3.70
06 September 2009	-	-	-	-	-	-
15 September 2009	25 - 27 September 2009	17	-0.15	0.32	4.32	4.85
Post-Season Survey	25 - 27 September 2009	17	-0.15	0.25	4.32	4.87

Tab. 1 - Summary of TLS Survey Parameters

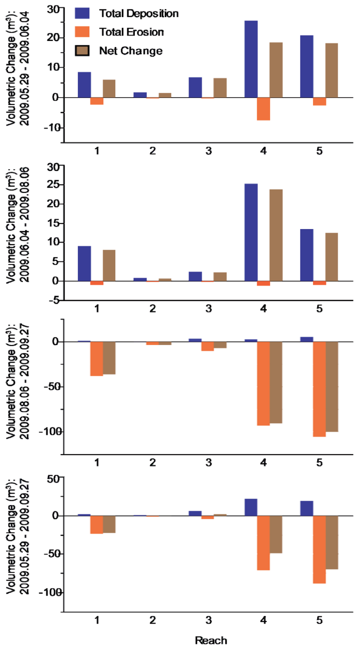

Fig. 3 - Volumetric change calculated for each channel reach by debris-flow event. A) 02 June 2009; B) 26 July 2009; C) 15 September 2009; D) Total seasonal change

Event	Reach	Area (m^2)	Total Deposition (m^3)	Total Erosion (m^3)	Net Volumetric Change (m^3)	Mean Gradient (%)	Particle-scale Roughness (%)	Channel-scale Roughness (%)
Pre-Season Survey	1	111.79	-	-	-	30.1%	16.1%	14.3%
	2	29.72	-	-	-	56.1%	20.9%	28.9%
	3	44.02	-	-	-	16.2%	33.4%	25.8%
	4	152.00	-	-	-	27.7%	45.1%	25.1%
	5	198.77	-	-	-	25.1%	22.8%	13.5%
2-Jun-2009	1	111.79	2.38 ± 0.17	8.45 ± 0.24	6.07 ± 0.42	29.8%	17.3%	16.0%
	2	29.72	0.21 ± 0.02	1.85 ± 0.09	1.64 ± 0.11	52.6%	21.8%	30.5%
	3	44.02	0.21 ± 0.03	6.70 ± 0.13	6.49 ± 0.16	21.3%	35.3%	23.9%
	4	152.00	7.45 ± 0.16	25.70 ± 0.39	18.25 ± 0.57	27.8%	32.2%	24.5%
	5	198.77	2.53 ± 0.21	20.67 ± 0.52	18.15 ± 0.74	25.3%	22.5%	16.9%
26-Jul-2009	1	111.79	1.02 ± 0.10	9.11 ± 0.30	8.08 ± 0.41	29.8%	17.8%	14.8%
	2	29.72	0.19 ± 0.03	0.88 ± 0.08	0.69 ± 0.11	52.6%	19.6%	28.6%
	3	44.02	0.22 ± 0.04	2.41 ± 0.12	2.19 ± 0.16	21.3%	34.0%	23.9%
	4	152.00	1.26 ± 0.13	25.12 ± 0.42	23.86 ± 0.56	28.8%	30.0%	22.3%
	5	198.77	0.99 ± 0.14	13.47 ± 0.58	12.47 ± 0.74	25.2%	18.9%	13.3%
15-Sep-2009	1	111.79	37.60 ± 0.49	1.21 ± 0.05	-36.40 ± 0.54	29.9%	22.3%	22.3%
	2	29.72	3.07 ± 0.13	0.04 ± 0.01	-3.03 ± 0.14	56.1%	22.6%	29.3%
	3	44.02	9.97 ± 0.14	3.38 ± 0.07	-6.60 ± 0.21	22.6%	33.0%	25.8%
	4	152.00	92.75 ± 0.66	2.33 ± 0.07	-90.42 ± 0.74	28.9%	41.4%	32.9%
	5	198.77	105.11 ± 0.80	5.31 ± 0.16	-99.80 ± 0.96	24.9%	25.7%	22.8%
Seasonal Change	1	111.79	23.86 ± 0.49	1.61 ± 0.05	-22.25 ± 0.54	-	-	-
	2	29.72	0.95 ± 0.08	0.23 ± 0.06	-0.71 ± 0.14	-	-	-
	3	44.02	4.01 ± 0.10	6.09 ± 0.11	2.08 ± 0.21	-	-	-
	4	152.00	70.47 ± 0.43	22.16 ± 0.30	-48.31 ± 0.74	-	-	-
	5	198.77	88.14 ± 0.73	18.96 ± 0.23	-69.18 ± 0.97	-	-	-

Tab. 2 - By channel reach, the calculated volumetric change and measured channel morphometry

volumetric change, and subsequent changes in channel morphometry for the five analyzed reaches organized by storm date. We also present the net changes that occurred throughout the entire summer season.

02 JUNE 2009

The debris flow event of 02 June 2009 occurred in response to 9.9 mm of rainfall over 5 hours. A rain gage at the upper station recorded a maximum 10-minute intensity of 9.1 mm/hr at 14:05, approximately 2 hours before the first debris flow surge recorded at the upper station (see McCoy *et alii*, this volume). Field reconnaissance suggests that the rainfall was produced by a small, isolated thunderstorm in the steep upper basin, and the measured rainfall may significantly underestimate the actual rainfall conditions that initiated the flow.

A repeat TLS survey conducted on 04 June 2009 provided data for the quantification of topographic change associated with the debris-flow event (Fig. 2a). The event was largely depositional. The surveyed reaches experienced 12.8 m^3 of total erosion, 63.4 m^3 of total deposition, and a total sediment increase of 50.6 m^3. Each reach experienced net aggradation. The greatest amounts (by height and volume) of deposition occurred in Reach 4 at the lower portion of the reach below the middle station (Fig. 2a), and the upper portion of Reach 5. Erosion was limited to two small areas of the channel within Reaches 4 and 5. Maximum erosion of the pre-event surface occurred in Reach 4, and was spatially coincident with the steepest portion of the surveyed channel and a large bank and hillslope failure. Calculations of net erosion and deposition for each of the five analyzed reaches are shown in Figure 3 and Table 2.

GIS analysis revealed minor changes in the morphometry of the channel following the debris flow (Tab. 2). Mean channel gradient remained virtually constant for Reaches 1, 4 and 5. Mean channel gra-

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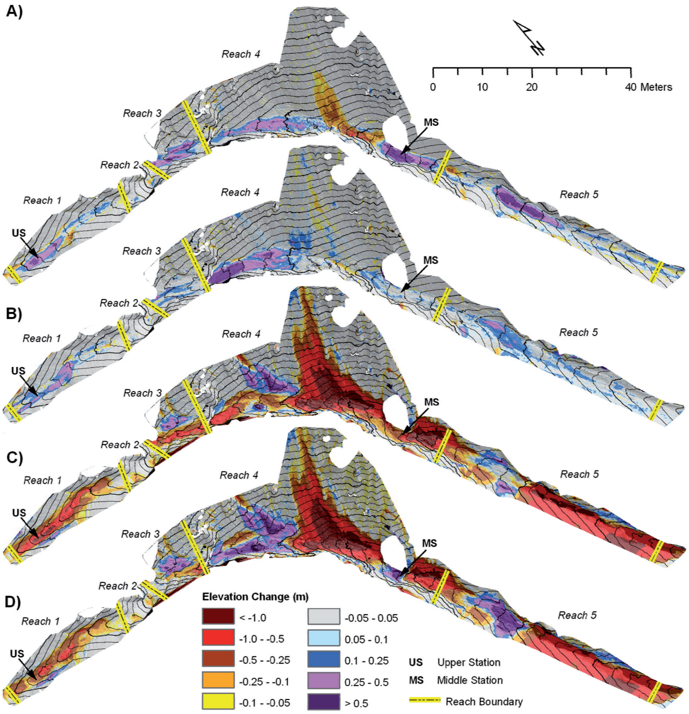

Fig. 2 - Changes in elevation measured during TLS surveys associated with A) 02 June debris-flow event; B) 26 July 2009 debris-flow event; C) 15 Sepetember 2009 debris-flow event; C) entire 2009 debris-flow season. Contour interval is 1 m. Flow direction is from left to right

dient decreased in Reach 2 and increased in Reach 3. Particle-size scale surface roughness increased in Reaches 1, 2 and 3, and decreased in Reaches 4 and 5. Reach 4 experienced the greatest decrease in particle-scale roughness, reflecting the removal of coarse clasts that were previously present in the eroded area. Channel-scale roughness increased in Reaches 1, 2 and 4, and decreased in Reaches 3 and 4. The increase noted in Reaches 1, 2 and 4 is attributed to the observed deposition of terminal lobes and levees. The decrease in roughness in Reach 3 is attributed to the observed development of a smooth, U-shaped bed between levees. Channel-scale roughness decreases evident in Reach 4 are attributed to an observed general smoothing of the channel in both the zones of erosion and deposition.

26 JULY 2009

The passage of the first surge of debris-flow material during the second documented event occurred around 7:12AM on 26 July in response to 10.7 mm of rainfall over 78 minutes (see McCoy *et alii*, this volume). The post-event survey was conducted on 03-04 August (Fig. 2b). This debris flow was almost exclusively depositional (Figure 3 and Table 2), with the channel experiencing a total of 51.0 m^3 of deposition and only 3.7 m^3 of erosion. The greatest amount of deposition was located in the uppermost portion of Reach 4, just below the boulder step (Fig. 2b). Erosion was confined to two small areas in Reach 1.

Channel-bed gradient remained similar, with Reaches 1, 2, 3 and 5 experiencing almost no changes in gradient (Tab. 2). Reach 4 experienced a slight increase in gradient, reflecting the influence of the steep front of the terminal lobe that was deposited in the uppermost section of the reach.

Particle-scale roughness decreased in all reaches except Reach 1 (Tab. 2). The increase in Reach 1 is attributed to the introduction of coarse clasts on the front of the freshly-deposited terminal lobe. Deposition in all other reaches created relatively smooth surfaces of debris-flow terminal lobes. All reaches experienced a decrease in channel-scale roughness, reflecting a general smoothing of the surface as material filled depressions produced during the previous debris flow.

06 SEPTEMBER 2009

No specific topographic information was collected regarding the 06 September 2009 debris flow event. This event occurred at 14:05 in response to 6.3

mm of rainfall over approximately 45 minutes.

Flow stage recorded at channel monitoring stations suggested a moderately-sized debris flow, with peak stages of 0.53 meters at the upper station, and 0.80 meters at the middle station. Video camera footage was not available for the upper reaches, and video of the lower reach suggested a modest amount of deposition. No field reconnaissance was conducted before the next debris flow occurred on 15 September 2009.

15 SEPTEMBER 2009

The 15 September 2009 debris flows were the most significant event of the summer in terms of precipitation, flow stage and bed stress (McCoy *et alii*, this volume). This debris flow event initiated after 24.6 mm of rainfall over a period of 115 minutes. A TLS survey of the post-event topography was conducted on 29 September 2009 (Fig. 2c). The greatest amount of topographic change for the summer was recorded during this inter-survey period, which included both the 06 and 15 September debris flows. These flows resulted in significant erosion of the channel bed, with 248.5 m3 of sediment removed from the channel, and only 12.3 m3 of deposition. All channel reaches experienced net erosion with Reach 5 experience the greatest volumetric loss (Fig. 3 and Tab. 2). The largest amount of erosion relative to the prior survey occurred in Reach 4, in the same general location of the area of greatest erosion during the 02 June event. In both cases, this was spatially coincident with the steepest channel gradient and adjacent to a large failure of bank and hillslope material. Nearly the entire length of Reach 1 was scoured to bedrock, though some channel loading had occurred prior to the TLS survey from rockfall and dry-ravel processes.

This event produced minor changes in mean channel gradient (Tab. 2). Reaches 2 and 3 both experienced an increase in channel gradient, while gradient remained virtually unchanged for Reaches 1, 4, and 5. Gradient increases in Reach 2 reflect the removal of fill on the bedrock step. Reach 3 increases in gradient reflect the observed channel adjustment as material at the top of the boulder step was removed.

Increases in roughness at the particle-scale were identified for all reaches with the exception of Reach 3 (Tab. 2). Here, the relatively smooth pre-event surfaces of debris-flow deposits were eroded, resulting in a surface of coarser clasts. Channel-scale roughness increased in all reaches. This reflects the removal of the relatively smooth channel fill deposited during the previous event, and the observed development of knickpoints in Reaches 4 and 5, presumably during the water-rich recessional flow of the debris flow.

SEASONAL CHANGES

Seasonal changes were quantified by comparing topographic data from the 29 May and 29 September TLS surveys (Fig. 2d). Overall, the analyzed channel lost 138.4 m3 of material over the season. Of the five reaches, only Reach 3 experienced net deposition (Fig. 3 and Tab. 2). The greatest positive changes in surface elevation were identified in Reach 3, where the channel adjusted to account for the development of the boulder step during the previous summer. Negative topographic change was at its greatest at the steepest section of Reach 4 and the lower half of Reach 5. In both cases, these areas were immediately adjacent to large failures of bank and hillslope material.

Mean channel bed gradients were similar between pre- and post-season surveys (Tab. 2). Reaches 1, 4 and 5 maintained a fairly constant mean gradient, while Reach 3 experienced an increase in gradient during each debris flow. This increase can be attributed to the channel adjusting to the development of the 2-m-high boulder step during a debris flow in early October of 2008.

Particle-scale roughness increased in Reach 1, decreased in Reaches 4 and 5, and remained relatively unchanged in Reaches 2 and 3. The increase in particle-scale roughness in Reach 1 reflects the removal of fine-grained colluvial fill that was present at the onset of the debris flow season. Decreases in particle-scale roughness in Reaches 4 and 5 reflect the removal of coarse material in the lower portion of Reach 4 and upper portion of Reach 5.

DISCUSSION

Analysis of high-resolution topographic data derived from multiple TLS surveys quantified how sediment is transported during both individual debris flow events and in response to a season of debris-flow activity that included four debris-flow events. The survey data clearly demonstrate that the locations and magnitudes of channel erosion and deposition vary from event to event. These findings are in agreement with Chen *et alii* (2005) who identified channel locations that experienced both erosion and deposition

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during multiple debris flows in China. In our study, Reaches 4 and 5 exhibited markedly different responses during the three documented events. The upper portion of Reach 4 (just below the boulder step) experienced deposition during the first two events, and erosion in response to the larger 14 September debris flow. Material was eroded from the steep middle portion of Reach 4 during the 02 June and 15 September debris flows, and deposited during the 26 July event. Large bank failures were observed in this reach following the June and September events, but not following the July event. Reach 5 experienced net deposition during the first two debris-flow events and a substantial amount of erosion during the 15 September event. These findings highlight the importance of smaller events as sources of sediment for subsequent larger debris flows. For the entire season, the greatest net erosion occurred in areas where material was deposited during the smaller events, such as in Reach 4 below the boulder step and below the middle channel monitoring station, and in Reach 5.

Analyses of morphometric data reveal unique insights into the evolution of channel gradient and roughness in response to multiple debris flow events. While there were some event-to-event fluctuations in gradient within the study reaches, analysis of seasonal changes show that mean channel-reach gradient remained fairly constant over this longer time period. The exception, however, occurred in Reach 3, which exhibited a seasonal decrease in channel gradient. This exception is attributed to channel response to the observed development of a boulder step during the fall of 2008. Because the gradients of the other reaches (both colluvial and bedrock) remained fairly constant over the season despite significant amounts of erosion, we conclude that channel gradients are adjusted to the high sediment-transport rates and debris flows in the study basin, at least during the period of record.

Measurements of roughness showed more variability than did those of channel gradient, with changes occurring at both particle- and channel-scales in response to different flow events. In general, however, roughness at both scales increased between May and September, although different responses were exhibited to individual events. The relative magnitudes of the debris flows as well as the amount of erosion or deposition influence both the particle- and channel-scale roughness measures.

The spatial patterns of erosion, deposition, and net volumetric change that we measured/quantified could not have been consistently predicted from pre-debris flow measurements of channel gradients or roughness. Linear regression identified no significant relation (r2 < 0.017 for all three parameters). Although changes in roughness and particle size impose new boundary conditions on subsequent debris flows (Benda and Dunne, 1997), it is apparent that other factors, such as water content, flow mechanics and rheology, also exert a significant influence on the ultimate response of the channel to the debris flow. As such, further research regarding the spatial and temporal patterns of debris-flow erosion and deposition must incorporate both morphometric data and information regarding flow properties.

CONCLUSIONS

We have documented the morphometric changes of a natural channel in response to multiple debris flow events during the summer of 2009. High resolution terrestrial laser scanning data permits the evaluation of these changes with very high accuracy and precision. Each monitored channel reach experienced erosion, deposition, and both net volumetric gains and losses during the summer debris flows. Overall, the channel experienced a net erosion of 276.8 m^3 of material in response to the four events of the season. Local variations in channel morphometry were related to the selective movement of particular grain sizes, the occurrence of channel bank failures, and the development of knick points. Mean channel-reach gradient stayed constant throughout the season, indicating a geomorphic equilibrium with the high sediment-transport rates and frequent debris flows that occur in the study basin. Examination of relationships between the magnitude of erosion and deposition yielded no strong correlations with channel reach gradients of roughness measures, indicating that point-specific predictions of locations or magnitudes of erosion or deposition cannot be adequately derived from statistical analyses of pre-event channel gradient or topographic roughness alone. Instead, a combination of high-resolution topographic changes and process information from in-situ measurements of flow dynamics may be necessary to better understand the relationships between debris-flow process mechanics, changes in surface form, and debris-flow magnitude. At Chalk Cliffs, we are building an extensive dataset of both process-oriented measurements and changes in topography associated with numerous debris-flow events (McCoy et al., 2010, McCoy et al., this volume). Further analysis of this unique combination of both datasets presents an opportunity to ultimately quantify the link between debris-flow processes and observed changes in the morphometry of natural channels.

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