Exhumation by debris flows in the 2013 Colorado Front Range storm

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ABSTRACT

The relative importance of extreme events in the long-term exhumation of landscapes is difficult to determine; the degree to which modern records capture long-term mean process rates is therefore commonly unknown. In September 2013, a massive precipitation event in the Front Range of Colorado (USA) triggered over 1100 landslides and debris flows in a historically sedate landscape. Here we employ topographic differencing, utilizing repeat aerial lidar, to quantify net sediment transport volumes in 120 of these mass movements within an area of 102 km² west of Boulder, Colorado. Comparing our results against published long-term erosion rates, we find that these mass movements evacuated the equivalent of hundreds to thousands of years of hillslope weathering products. We conclude that (1) rare debris flows perform the majority of sediment transport and channel erosion within steep channels along the eastern edge of the Front Range, potentially explaining discrepancies between modern sediment yields and long-term erosion rates in such settings, and (2) the high spatial density of debris flows along the corridors bounding steep canyons suggests that the landscape switches to debris-flow dominance as knickpoints pass headward along the canyons.

INTRODUCTION

Landscapes evolve over time scales that greatly exceed the period of historical records. It is therefore important to understand the degree to which modern observations capture the full range of geologically formative processes and process rates. A growing number of at-a-site comparisons between long-term (10^4–10^6 yr) denudation rates and modern sediment yields have shown that yields differ significantly over different time scales; relatively higher modern loads have been attributed to anthropogenic factors (Brown et al., 1998; Vanacker et al., 2007; Perroy et al., 2012), while relatively lower modern loads have been taken to indicate that infrequent extreme events, missing in modern records, have performed a significant fraction of the total geomorphic work (Kirchner et al., 2001; Carretier et al., 2013). Documenting the geomorphic impact of rare, extreme events is difficult.

In this paper, we use repeat aerial lidar to quantify the erosional impact of a precipitation event that inundated the Front Range of Colorado (United States) in September 2013. The storm triggered over 1100 landslides and debris flows in a 3430 km² area (Coe et al., 2014). The number of hillslope failures in a single event represent unprecedented activity for the region in its ~150 yr of written history. Comparing the volumes of sediment evacuated against published erosion rates derived from sediment ^{10}Be concentrations, we demonstrate that these rare debris flows are likely the dominant sediment-transport and channel-eroding process for the steep inner canyons of the Front Range.

REGIONAL SETTING AND THE 2013 STORM

The Colorado Front Range is a Laramide range, with a core of Precambrian crystalline rocks (gneiss and granodiorite) uplifted adjacent to Mesozoic sedimentary rocks (Dickinson et al., 1988). The topography reflects rapid late Cenozoic exhumation of the western edge of the High Plains, lowering local base levels for the streams draining the range. This initiated incision of narrow canyons in the crystalline rock through knickpoint propagation upstream from the contact of soft and hard rocks at the mountain front (R.S. Anderson et al., 2006; S.P. Anderson et al., 2012a). Present knickzones are many kilometers upstream from the contact (Fig. 1). The canyon walls are composed of steep slopes, with thin (<0.5 m) to incomplete soil cover, that are increasingly dissected by low-order channels with distance downstream of the master river knickzone.

The 2013 storm began on 9 September with the arrival of a slow-moving cyclonic system drawing moisture from the Gulf of Mexico. Over five days, the storm dropped between 200 mm and 450 mm of rain along an ~100-km-wide swath of the Front Range (Fig. 1). This precipitation, equivalent to the annual average for much of the region (Gochis et al., 2014), caused widespread flooding and numerous mass-wasting events. Although mass movements are common in Colorado (Jochim et al., 1988; Godt and Coe, 2007), this event was remarkable in the number of failures and for impacting every major river in the area (Coe et al., 2014).

METHODS

Pre-event aerial lidar, acquired in August 2010 by the National Center for Airborne Laser Mapping (S.P. Anderson et al., 2012b), was subtracted from post-event lidar, acquired by Quantum Spatial company for the U.S. Federal Emergency Management Agency in November 2013, to create a difference map. The study area is set by the 102 km² area of overlap of these data sets. Crystalline rocks underlie most of the area, while sedimentary rocks underlie hogbacks lining the eastern edge (Fig. 1). We used the difference map, confirmed by post-event aerial imagery and field checks, to outline mass movements and calculate their volume, V_{LS} (Fig. 2). For debris flows that scoured over a significant length, mean lowering was quantified at regular intervals down the channel centerline (e.g., Anderson and Pitlick, 2014). The lowering was integrated to yield net transport down channel and total exhumation, V_{DF} (Fig. 3). The area of overlap between adjacent independently processed flight lines in the 2013 survey allows us to estimate the mean and 95th percentile errors, which are 0.13 and 0.26 m³/m² respectively.

Published ^{10}Be-derived erosion rates for the low-relief crystalline surface above the knickzone are 20–30 mm/k.y. (Foster et al., 2015). As mass movements in the crystalline rock occurred exclusively within steep canyon-wall basins downstream of the knickzone, however, we used published ^{10}Be-derived mean erosion rates for these areas of 30–60 mm/k.y. (Dethier et al., 2014). In these basins, erosion rates are linearly correlated with mean basin slope; we used a linear regression to compute a local long-term erosion rate for each basin containing at least one mass movement. From this, we estimate the time, T, it would take to produce the material evacuated by the debris flows (Fig. 2). As no long-term erosion rate estimates exist for the sedimentary rock, we are unable to place erosion from those failures in a long-term context.

RESULTS

We identified a total of 120 mass movements, 36 located on crystalline rock and 84 in sedimentary rock. The majority initiated very high in drainages on roughly planar colluvium-mantled slopes of between 25° and 40° (Fig. 1). About 90% initiated as shallow landslides, with failure depths of 0.5–1 m. The remaining 10% were progressively bulked debris flows or bank and road-cut slumps. The landslides transformed

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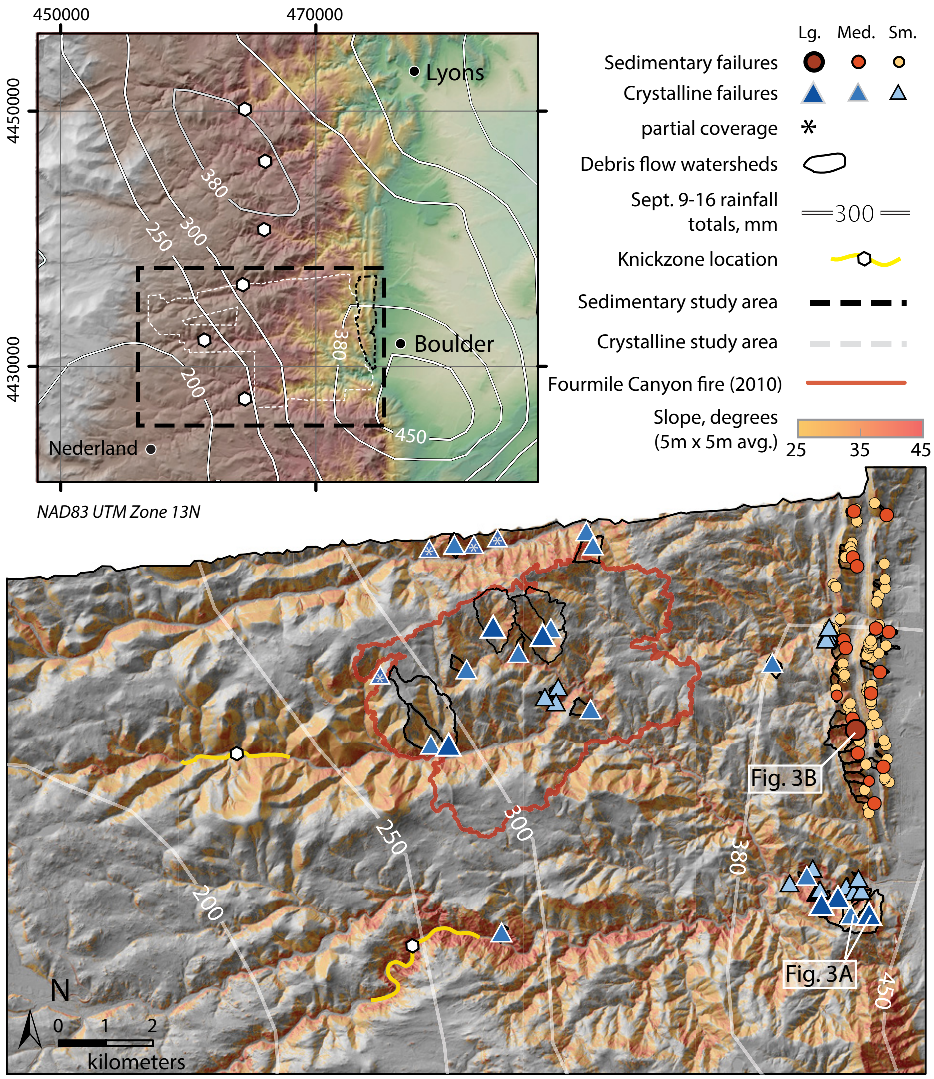

Figure 1. Overview maps showing mapped failure locations in Colorado, USA. Top map shows topography and precipitation isopleths. Lidar difference analysis was performed in study areas in dashed outlines within box. Lower map shows failure locations in relation to slope map, knickzones, Fourmile Canyon fire area, and precipitation. Failure size is based on total volume of material mobilized: small (Sm.), <500 m³; medium (Med.), 500–4000 m³; large (Lg.), >4000 m³. Symbols with gray asterisk indicate failures that were identified but were located partially or entirely outside of lidar overlap, precluding volume estimations. Slope color ramp bounds of 25° and 45° correspond to range of slopes that produced failures. Failures mapped in Figures 3A and 3B are identified. Precipitation data obtained from National Oceanic and Atmospheric Administration (http://www.esrl.noaa.gov/psd/boulder/flood2013/precipplots/). UTM—Universal Transverse Mercator.

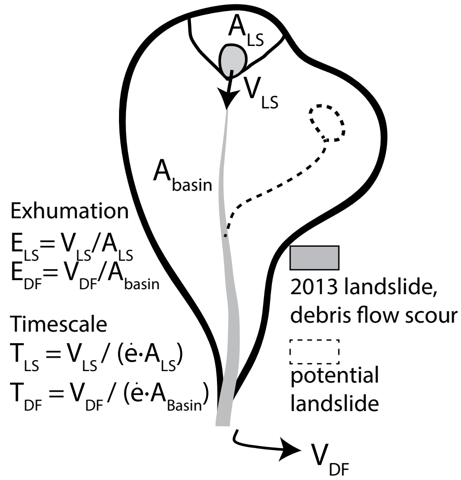

Figure 2. Conceptual diagram of hollow-channel systems, with equations used to translate landslide (LS) and debris-flow (DF) volumes into equivalent lowering rates (*E*) and recurrence times of hillslope erosion, where *T* is recurrence time scale, ė is erosion rate, *A* is contributing area, and *V* is volume of material evacuated from either channels or hollows.

into debris flows where the mobilized material entered convergent areas, which occurred in ~70% of all mass movements in the crystalline region and 40% in the sedimentary. The majority of the remaining shallow landslides in sedimentary rock did not transform into debris flows.

All debris flows in the crystalline region occurred in small canyon-wall basins and debouched from steeply inclined paths directly into trunk streams (e.g., Fig. 3A). Simultaneous flood-stage stream flow was sufficiently energetic to maintain mobility of nearly all of the material; no significant debris fans were constructed, and the majority of the material appears to have exited the mountain front. In contrast, mass movements on sedimentary-rock hogback ridges commonly deposited fans in the inter-ridge valleys (e.g., Fig. 3B).

No strong correlation between local slope and drainage area exists at the sites of landslide initiation (Fig. DR1 in the GSA Data Repository[1]). This result is consistent with prior work in Colorado (Godt and Coe, 2007; Henkle et al., 2011; Coe et al., 2014), implying strong control of failure location by local conditions (see the discussion in the Data Repository). The distribution of slope aspect at failure sites was indistinguishable from that of the underlying topography (Fig. 4). This contrasts with the south-facing aspect bias over the 30-fold larger area analyzed by Coe et al. (2014) for the same event.

The size of individual mass movements ranged from 10 m³ to 21,000 m³. The 36 mass movements on crystalline rock evacuated a total of 77,000 m³, while the 84 failures mapped in the sedimentary subarea mobilized a total of 37,000 m³. Debris flows scoured to bedrock along their entire length, evacuating a relatively uniform sediment depth of 0.2–0.5 m (e.g., Figs. 3C and 3D; see distribution in Fig. DR2). Bedrock erosion was locally evident, although rarely dramatic; most of the lowering represented evacuation of stored sediments.

Basin-average lowering depths, E_{LS} (Fig. 2), ranged from 4 mm to 500 mm, with area-weighted averages for the crystalline and sedimentary regions of 16 mm and 21 mm, respectively (Fig. 4B). Note that these averages are only for basins that contained mass movements, which compose only 7% of the crystalline rock area and 21% of the sedimentary rock area. Given both the slightly greater basin-mean lowering and the higher density of failures, the sedimentary region as a whole lowered three to four times more than the crystalline region during this event. In both regions, mean lowering generally decreased with increasing contributing area (Fig. 4B); empirically, this reflects net transport vol-

[1]GSA Data Repository item 2015136, discussion of slope-area thresholds, landslide and channel scour depths, volume-drainage area relationships and debris flow erosion law, volume and length-drainage area relationships, and channel recharge and diffusivity, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

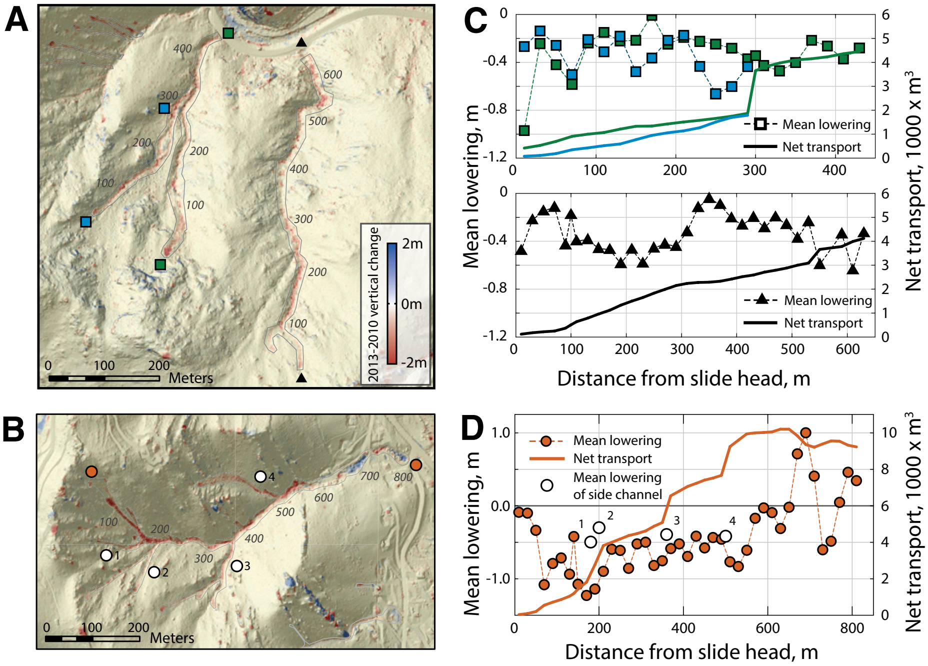

Figure 3. Example failures and morphologic budgeting results. A,B: Digital elevation model of difference shows debris-flow paths (with distances in meters) in crystalline rock (A) and in sedimentary rock (B). Colored symbols mark head and toe in corresponding plots in C and D. Locations are shown in Figure 1. Debris flows in A are among the largest within the study area, scoured from their initiation points to Boulder Creek, which curves across top of image. Smaller slides are visible in upper left. Note deposition in B at distal end of tracks. C,D: Mean lowering and integrated transport at ~20 m intervals along debris-flow paths depicted in A and B, respectively.

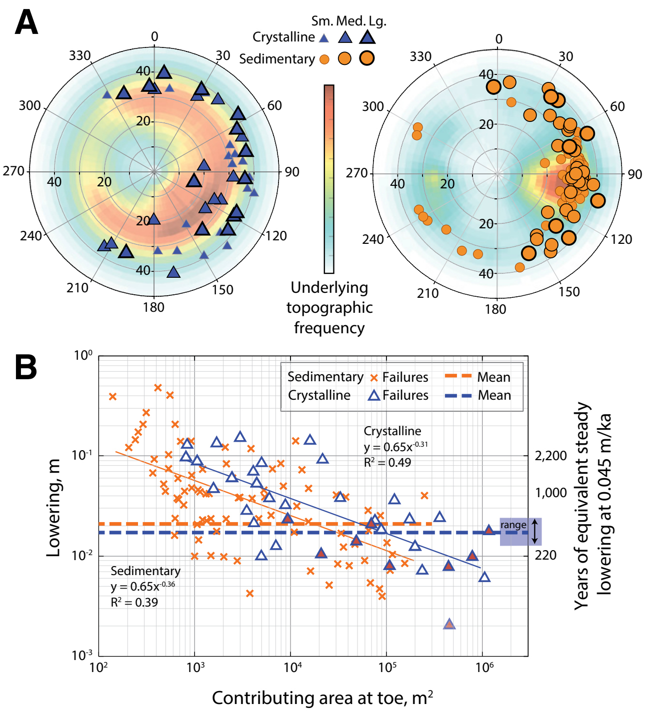

Figure 4. Debris-flow initiation characteristics and accomplished lowering. A: Polar plots showing aspect of initiation sites (in degrees) on polar axis and mean slope (in degrees) on radial axis. Designations of small (Sm.), medium (Med.), or large (Lg.) refer to volume of entire debris flow (V_{DF}), with size breakdowns as in Figure 1. Background color map shows relative frequency of slope–aspect combinations in underlying topography. B: Basin-averaged lowering (in meters) of failures plotted against contributing area to failure toe. Lines show power-law regression through data for sedimentary and crystalline areas. Dashed lines show area-weighted average lowering of 0.016 m (crystalline region) and 0.020 m (sedimentary region). For crystalline rock, for which long-term erosion rates from ^{10}Be are available, the mean lowering is translated into equivalent time of lowering at steady 45 mm/k.y. lowering rate (right axis); shaded box shows range for lowering rates of 30–60 mm/k.y. (range of Dethier et al., 2014). Slides within Fourmile Canyon fire area (Graham et al., 2012) are filled red. One outlier, a landslide in mine tailings, is grayed.

umes that increase linearly with channel length (owing to relatively constant scour depths and channel widths), while drainage area increases as channel length to the 1.6 power.

Comparing mean basin-lowering depths with ^{10}Be-derived long-term erosion rates in the crystalline rock, we estimate that mass movements evacuated the equivalent of 150–2200 yr (median 440 yr) of hillslope weathering products; the area-weighted mean is 300 yr (Fig. 4). The uncertainties in our volume estimates and in the ^{10}Be-based erosion rates yield a total uncertainty of ±50%.

DISCUSSION

Debris flows have rarely been recorded in the Front Range (Costa and Jarrett, 1981; Jarrett and Tomlinson, 2000). The 2013 storm is historically unprecedented in its rainfall total, area impacted, and number of failures (Coe et al., 2014). The only record approaching this is associated with a July 1999 convective storm in the central Front Range in which 43 mm of rain (35 mm in 2 h) yielded 480 debris flows in a 240 km² alpine area (Godt and Coe, 2007). We ask what fraction of the geomorphic work is accomplished by such rare events (Wolman and Miller, 1960; Baker, 1977; Meyer et al., 2001).

In our study area, basins in crystalline rock with failures composed 7% of the area. On average, ~20 mm of surface lowering occurred in these basins, or ~1.4 mm of lowering averaged over the whole area (~30 yr of weathering products from the crystalline study area overall, assuming the ^{10}Be erosion rate of 0.045 m/k.y.). To keep pace with weathering, debris-flow export of sediment could be accomplished either by numerous 1999-style convective storms that produce failures in a few basins, or larger-footprint 2013-style storms with ~300 yr recurrence intervals.

Short-term sediment yields commonly underpredict long-term erosion rates based upon ^{10}Be concentrations in sediment. This has been attributed to short gaging records that rarely include exceptional events (Kirchner et al., 2001). Our results suggest that Colorado Front Range gaging records would have to include these hundred- to thousand-year exhumation events in order to match the long-term ^{10}Be rates, in accord with rare events dominating erosion in more arid regions (Carretier et al., 2013).

Post-fire debris flows, important in erosion of semi-arid regions (e.g., Pierce et al., 2004), commonly initiate through progressive sediment bulking during overland flow (Cannon et al., 2010; Gartner et al., 2008; Santi et al., 2008). In our study, the density of failures was similar in unburned areas and in the 2010 Fourmile Canyon fire area (Fig. 1), in accord with observations across the region (Coe et al., 2014). Most failures appeared to be saturation related, attributed to the persistent precipitation rather than to post-fire changes in infiltration. Such behavior in semi-arid landscapes has also been seen in rain-on-snow events (Meyer et al., 2001).

Finally, we note that the spatial distribution of mass movements was strongly controlled by the location of colluvium on slopes greater than ~25°. In the Front Range, these slopes occur almost exclusively along the canyons where low-order tributaries have steepened in response to erosion of the master stream by knickzone passage (S.P. Anderson et al., 2012a). The passage of this knickzone acts as a switch, turning on debris-flow processes in its wake. Debris flows not only serve as the mechanism by which sediment is removed from this steepened landscape, but also scour into rock, promoting the incision of tributaries away from the trunk stream, further dissecting this outer margin of the range.

CONCLUSION

We used repeat aerial lidar to estimate the volumes of sediment mobilized in 120 debris flows and landslides that occurred during the September 2013 Front Range storm. The exhumed volumes correspond to basin-averaged lowering on the order of 10 mm, representing the export of hundreds to thousands of years of weathering products. These results both highlight the importance of rare events in long-term erosion of this landscape, and help to explain why modern sediment yields may greatly underestimate long-term denudation rates in such settings. Debris flows dominate sediment export from storage on the steep hillslopes that bound the canyons draining the Front Range.

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