# New insights into debris-flow hazards from an extraordinary event in the Colorado Front Range

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## ABSTRACT

Rainfall on 9–13 September 2013 triggered at least 1,138 debris flows in a 3430 km$^2$ area of the Colorado Front Range. The historical record reveals that the occurrence of these flows over such a large area in the interior of North America is highly unusual. Rainfall that triggered the debris flows began after ~75 mm of antecedent rain had fallen, a relatively low amount compared to other parts of the United States. Most flows were triggered in response to two intense rainfall periods, one 12.5-hour-long period on 11–12 September, and one 8-hour-long period on 12 September. The maximum 10 min. intensities during these periods were 67 and 39 mm/hr. Ninety-five percent of flows initiated in canyons and on hogbacks at elevations lower than a widespread erosion surface of low slope and relief (<2600 m). These flows were on steep (>25°), predominantly south- and east-facing slopes with upslope contributing areas <3300 m$^2$. Flows with the largest scars and longest travel distances occurred at elevations above 2600 m on steep slopes with contributing areas >3300 m$^2$. Areal concentrations of debris flows revealed that colluvial soils formed on sedimentary rocks were more susceptible to flows than soils on crystalline rocks. This event should serve as an alert to government authorities, emergency responders, and residents in the Front Range and other interior continental areas with steep slopes. Widespread debris flows in these areas occur infrequently but may pose a greater risk than in areas with shorter return periods, because the public is typically unprepared for them.

## INTRODUCTION

> *Most of the hazardous mass wasting along the Front Range is restricted to clearly defined geomorphic settings where problems have a rather high element of predictability.* —Wallace R. Hansen, U.S. Geological Survey, 1976, p. 106

> *We knew from our hydrology, meteorologists, and computer modeling how much rain in a given time period would result in specific cubic feet per second stream flow, and the flooding that would result from this stream flow. What took me by surprise were all of the side-hill landslides and debris flows that came into the main canyons and creek channels. The Office of Emergency Management, and local law enforcement and fire districts are worried, and are anxious for any data that can help them to prepare for future landslide incidents.*
> —Dan Barber, Boulder County Office of Emergency Management, 10 Jan. 2014 (pers. commun.)

The dichotomy of these statements illustrates the issue of debris-flow hazards in the Colorado Front Range. On one hand, geologists recognize where hazardous debris flows are most likely to occur. On the other hand, the localized nature of debris flows and their infrequent occurrence compared to other natural hazards create a situation in which residents and government officials are generally unaware of the threats they pose. During the week of 9–13 September 2013, the Front Range received a harsh reminder of the dangers posed by debris flows. During that five-day period, nearly continuous rainfall caused widespread debris flows and flooding in a 3430 km$^2$ area of the northern Front Range (Fig. 1). The combination of debris flows and flooding was responsible for eight fatalities and caused extensive damage to buildings, highways, railroads, and infrastructure. In Larimer, Boulder, and Jefferson Counties, the three mountainous counties affected by flooding and debris flows, 125 houses were destroyed and another 3,773 were damaged (Federal Emergency Management Agency [FEMA], written comm., 24 Feb. 2014). Three fatalities were attributed to debris flows (Godt et al., 2014). Most major canyon roads were closed from 12 September until the end of November 2013, causing major disruptions to the transport of people and goods and an adverse impact on tourism. Roads were rebuilt using US$450 million from the Federal Highway Administration Emergency Assistance Fund (Bennet, 2013a). Other recovery efforts in the three counties were funded by US$62.8 million from the Department of Housing and Urban Development (Bennet, 2013b), US$102.1 million from FEMA, and US$57.4 million from the National Flood Insurance Program.

Widespread, rainfall-triggered debris-flow events such as the one in the Front Range are expected in active orogenic mountain belts (e.g., Sidle and Ouchai, 2006), as well as in tectonically inactive mountain belts along coastlines (e.g., Wieczorek and Morgan, 2008). Hillslopes in active orogenic belts are presumed to be preferentially susceptible because they are uplifted, steepened, and loosened from ground shaking by earthquakes (e.g., Petley, 2012), whereas coastal areas are regularly impacted by large, intense storms fed by tropical moisture (e.g., Porter et al., 2011). The Colorado debris-flow event was extraordinary because (1) the Front Range is not an active orogenic mountain belt, and (2) a very large area well within the continental interior

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## Featured Article

### SCIENCE:

**Cover:** House damaged by a September 2013 debris flow in Big Thompson Canyon in the Colorado Front Range; deposit (foreground) covers U.S. Highway 34. Photo by Jonathan Godt, 20 Sept. 2013. See related article, p. 4–10.

## GSA News

### Erratum

In the August 2014 issue of *GSA Today*, science article co-author Mark R. Besonen was incorrectly listed with a middle initial of "T." The correct middle initial is "R." Please make a note of this for future citation; *GSA Today* regrets this error.

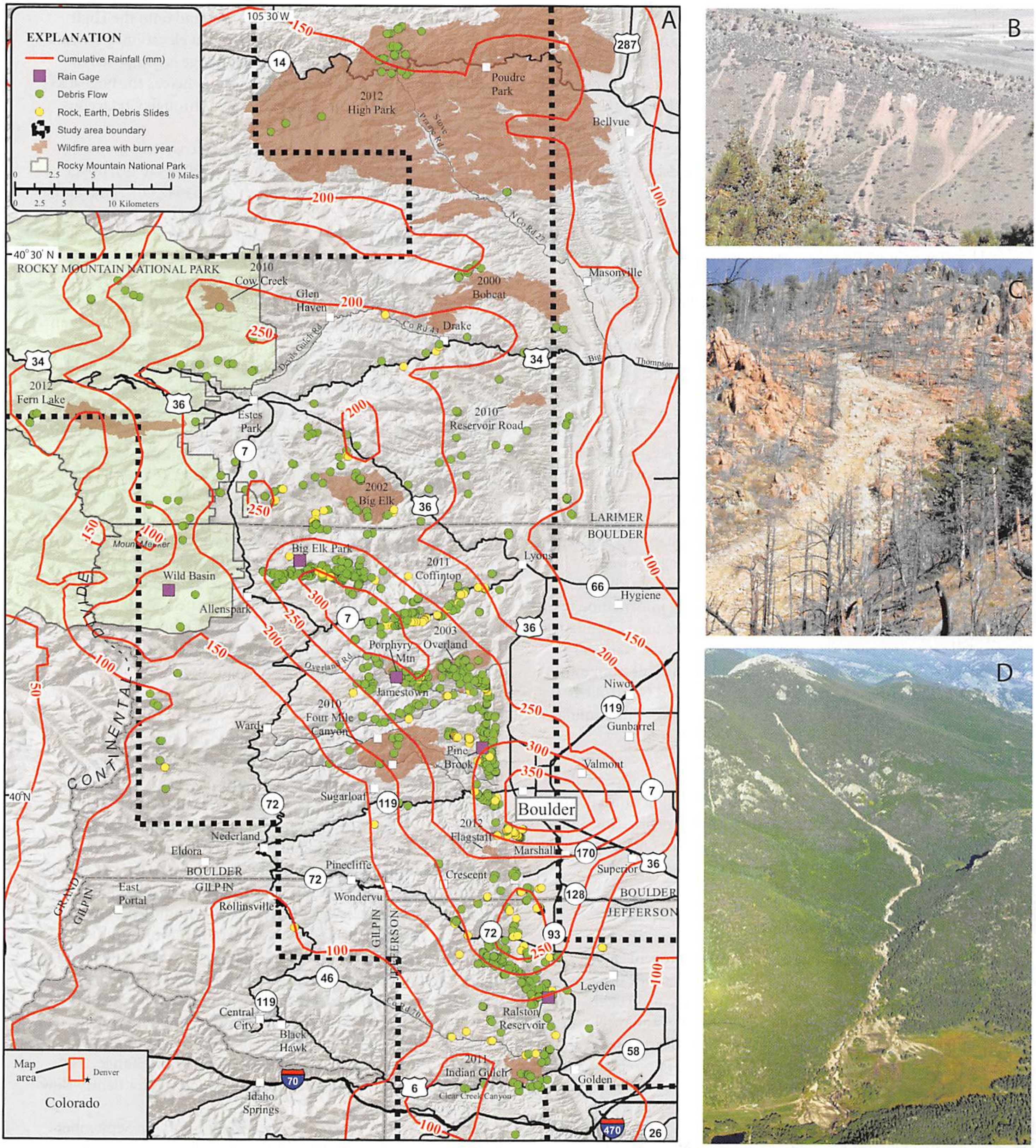

Figure 1. Diagram showing debris flows triggered by September 2013 rainfall. (A) Map of debris-flow locations (as well as rock, earth, and debris slides) overlain by contours of cumulative rainfall from 10 September at 6 p.m. to 13 September at 6 p.m. Number of mapped debris flows was 1138. Number of mapped rock, earth, and debris slides was 212. (B) Debris flows at the contact between the Morrison Formation and Dakota Group on the southwest side of a hogback near Ralston Reservoir; visible relief is ~90 m. (C) Debris flow in the Overland wildfire burn area on Porphyry Mountain; visible relief is ~150 m. (D) Debris flow on the east side of Twin Sisters Peaks near Allenspark; visible relief is ~1000 m.

of North America was impacted by prolonged rainfall fed by tropical moisture. We know of only one other similar-sized debris-flow event within the continental interior of the United States: the 1983 snowmelt-induced event along the Wasatch Front in Utah (Brabb et al., 1989). Historical debris flows in the Colorado Front Range have been triggered by rapid snowmelt and localized rainstorms—often thunderstorms fed by moisture from the North American Monsoon, which caused debris flows over relatively small geographic areas (<250 km$^2$; Shroba et al., 1979; Coe and Godt, 2003; Godt and Coe, 2007) compared to the area impacted in 2013.

The September 2013 event offers a historically unprecedented opportunity to examine and characterize debris flows that occurred over an extremely broad range in elevation, geology, and ecosystems. To begin this process, we examined debris flows in the field and mapped the flows using high-resolution (0.5 m pixel size), orthorectified satellite imagery available from Digital Globe Inc. For each debris flow, we mapped the initiation location and travel distance. For each initiation location, we recorded the topographic setting (i.e., open slope, swale, or channel) and whether the debris flow entered the channel network. Elevation, slope angle, and slope aspect for each initiation location were extracted from U.S. Geological Survey (USGS) 10-m digital elevation models (DEMs). Geologic units for ~95% of initiation locations were extracted from 1:100,000-scale geologic maps (Kellogg et al., 2008; Cole and Braddock, 2009). The remaining 5% were extracted from the 1:500,000-scale geologic map of Colorado (Tweto, 1979). We collected debris-flow timing information by interviewing residents and local authorities. We used cumulative rainfall estimates compiled and interpolated by the National Center for Atmospheric Research and storm rainfall from rain gages operated by the Urban Drainage and Flood Control District and the National Resources Conservation Service. The cumulative, spatially continuous rainfall was derived from the U.S. National Weather Service (NWS) Multi-Sensor Precipitation Estimate (MPE; Kitzmiller et al., 2013). Our analysis focused on identifying and characterizing the most important rainfall, topographic, and geologic variables that controlled debris-flow initiation locations, timing, and travel distances. We conclude with the implications of our work for future debris flows in the Front Range and similar steep settings.

## THE COLORADO FRONT RANGE

The Colorado Front Range was formed by orogenic uplift related to regional compression during the Laramide orogeny in the Late Cretaceous to early Tertiary (e.g., Dickinson et al., 1988). Since the early Tertiary, the occurrence, timing, and mechanisms of uplift are uncertain and controversial (e.g., Karlstrom et al., 2012). If uplift is currently ongoing, it appears to be epeirogenic in origin (e.g., Eaton, 2008).

The topography of the northern Front Range east of the Continental Divide consists of four major elements progressing from high to low elevations (Anderson et al., 2006): (1) the divide itself, which ranges in elevation from 3350 to 4300 m and was shaped by Pleistocene glaciers (Madole et al., 1998); (2) a widespread erosion surface of low slope and relief (Epis and Chapin, 1975) at elevations between ~2200 and 2750 m (Kellogg et al., 2008); (3) steep-walled canyons that cut this surface and drain eastward across the edge of the range front and onto the High Plains; and (4) hogbacks at the range front at elevations between 1550 and 1800 m. The core of the Front Range is composed of Proterozoic and Tertiary crystalline rocks, whereas the hogbacks are a sequence of upturned Pennsylvanian through Cretaceous sedimentary rocks.

The broad range in elevations spans five ecosystem zones: grassland (~<1830 m), lower montane (~1830–2440 m), upper montane (~2440–2835 m), subalpine (~2835–3475 m), and alpine (~>3475 m) (Marr, 1961). The dominant vegetation is coniferous forest between 1830 and 3475 m. Vegetation density, soil development, and regolith production are dependent on slope aspect, particularly on north- versus south-facing slopes in the montane zones. North-facing slopes have a higher density of trees (Marr, 1961) and more leached, colder soils (Birkeland et al., 2003) than south-facing slopes.

Previous research on debris flows in Colorado has indicated that slope aspect and elevation play a role in the frequency of debris-flow occurrence, but, because of a lack of widespread historical events, neither topic has been fully explored. Coe et al. (2003) analyzed debris-fan stratigraphy and historical records from 19 fans at elevations between 2200 and 3350 m along the east-west–trending Interstate-70 in the Front Range. They found that mean debris-flow recurrence intervals were consistently long (450–2640 yr) on north-facing slopes and wide ranging (7–2900 yr) on south-facing slopes. Costa and Jarrett (1981) separated Colorado into two debris-flow environments based on an elevation threshold of ~2300 m. They found that below 2300 m, frequent intense rainfall caused large water floods. Above 2300 m, they found that intense rainfall was less frequent and that both debris flows and water floods occurred in response to rainfall.

## ANTECEDENT RAINFALL

Observations indicate that moderate-to-intense rainfall is required to induce debris flows. Rainfall prior to moderate-to-intense periods of rain often plays a critical role in determining whether debris flows occur (e.g., Wieczorek and Glade, 2005), particularly debris flows that are mobilized from shallow landslides, as was the case in September 2013. Antecedent rainfall controls the initial moisture content of slope materials, which in turn affects the rate and depth of wetting during subsequent rainfall, as well as soil pore-water pressure. Minimum amounts of antecedent rainfall are a representation of the minimum field moisture capacity required of slope materials before moderate-to-intense storms can trigger debris flows (Wieczorek and Glade, 2005). Previous work has shown that minimum antecedent rainfall values are highly variable and depend on regional climate, soil properties, and vegetation. Because of the limited number of historical debris-flow events in the Colorado Front Range, the minimum amount of antecedent rainfall required for debris-flow initiation is undefined.

To evaluate the influence of antecedent rainfall in September 2013, we analyzed rainfall data from five rain gages at progressively increasing elevations (Fig. 2A). From lowest to highest elevations, the distribution of rain gages trended to the northwest, starting at Ralston Reservoir and ending at Wild Basin (Fig. 1A). The four lowest gages are event-recording gages, whereas the Wild Basin gage records data hourly. Cumulative summer rainfall prior

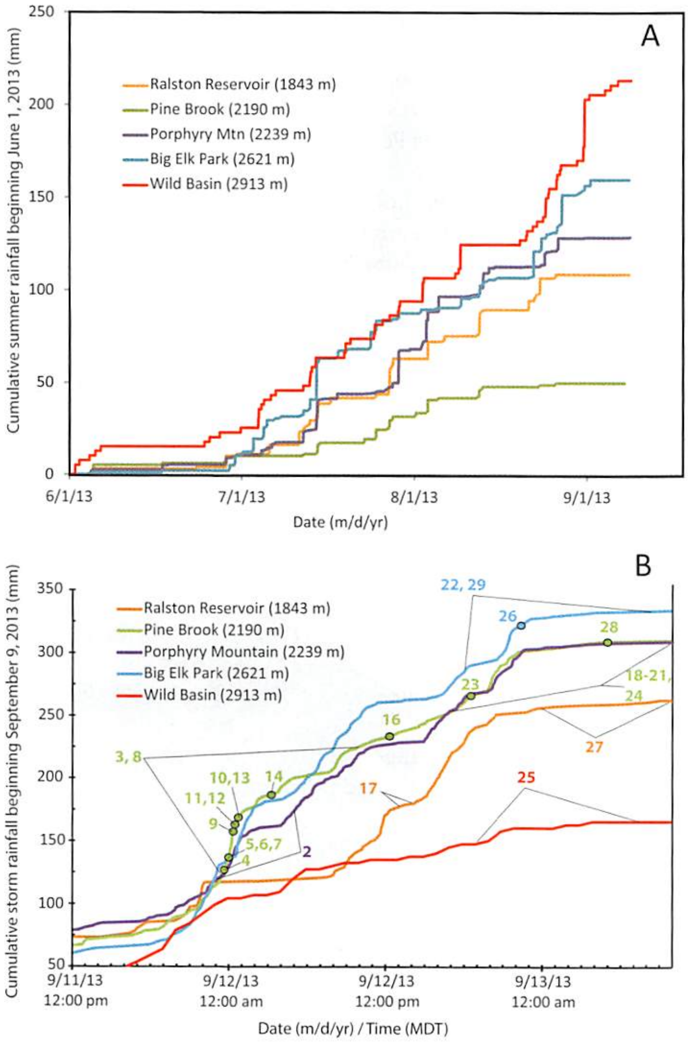

Figure 2. Rainfall measured at rain gages in the Front Range during the summer of 2013. (A) Cumulative antecedent rainfall prior to 9 September. (B) Rainfall and debris-flow occurrence from 11 to 13 September. Numbered circles are precise times of debris flows. Numbered zones are time ranges where debris flows were observed. Numbers correspond to descriptions of flows in Table DR1.

to 9 September ranged from 45 mm to 185 mm, with cumulative rainfall generally increasing with elevation (Fig. 2A). From 26 August to 8 September, elevations below ~2250 m were dry, but this period of dryness was progressively shorter at higher elevations (Fig 2A, ~1 week at 2621 m, ~2 days at 2913 m).

Based on the lack of rainfall in the two weeks prior to 9 September, we assume that the colluvial soil mantle at elevations below ~2250 m was "dry" prior to the start of rainfall at ~2:30 p.m. on 9 September. At these elevations, debris flows began at ~11:30 p.m. on 11 September (Table DR1 in the Data Repository[1]). In the 50 h time period between the start of rainfall on 9 September and the beginning of the moderate-to-intense triggering rainfall at ~4:30 p.m. on 11 September, from 75 to 85 mm of rain fell at elevations below 2250 m (Fig. 2B). We consider 75 mm a reasonable estimate of the minimum antecedent rainfall needed for subsequent debris flows. This amount of antecedent rainfall is relatively low compared to other regions of the United States where debris flows have been studied (e.g., western Oregon [>200 mm]; San Francisco [>250 mm]; Seattle [>180 mm] [Baum and Godt, 2010]).

## RAINFALL THAT TRIGGERED DEBRIS FLOWS

Rainfall from 9 to 15 September was exceptional because of its duration (7 days), large spatial extent, and record-breaking cumulative amounts (e.g., 230.6 mm, 292.6 mm, and 429.3 mm for 1-, 2-, and 7- day periods within the City of Boulder) (Lukas et al., 2013). This prolonged rainfall was caused by a nearly stationary low-pressure system centered near the southwest corner of Utah. (See Gochis et al., 2014, for a detailed meteorological description of the event.) Counterclockwise circulation of this system pulled monsoonal moisture from both the Pacific Ocean and the Gulf of Mexico. In northern Colorado, circulation around the low caused the flow of moisture to impact the Front Range from the east and southeast. Most of the rain fell between the afternoon of 11 September and the morning of 13 September (Fig. 2B). Documented times of 27 debris flows (Table DR1) were all during this time period.

The first period of rainfall that triggered debris flows was in the 12.5 h between 4:30 p.m. on 11 September, and 5 a.m. on 12 September (Fig. 2B). Rainfall during this period reached maximum 10 min intensities of 51, 67, 38, and 63 mm/hour at the Ralston Reservoir, Pine Brook, Porphyry Mountain, and Big Elk Park gages, respectively (Fig. 2B). Maximum 1 hr intensities at the Wild Basin gage were 15 mm/hr. Nearly half of the debris flows (12 of 27) with known times were near the Pine Brook rain gage during this period. Another 11 debris flows occurred during and after a second period of heavy rainfall in the eight hours between 3 p.m. and 11 p.m. on 12 September. Maximum 10 min intensities during this period were 22, 35, 30, and 39 mm/hour at the Ralston Reservoir, Pine Brook, Porphyry Mountain, and Big Elk Park gages, respectively (Fig. 2B). Maximum 1 h intensities at the Wild Basin gage were 8 mm/hr. Documented debris flows associated with this period of rainfall were more dispersed in elevation and time compared to debris flows associated with the first period (Fig. 2B). These dispersed debris flows included some of the largest (deepest scars and longest travel distances) in the study area (e.g., Fig. 1D, and numbers 25, 26, and 27 in Table DR1).

## DEBRIS-FLOW CHARACTERISTICS

All September 2013 debris flows began as discrete sliding masses of colluvial soil (slides) that liquefied and moved rapidly downslope. About 90% of slides had upslope contributing areas <3300 m$^2$ (Fig. DR1). Slopes measured at headscarps in the field ranged from 26 to 43°. Ninety-seven percent of slides initiated on

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[1] GSA supplemental data item 2014323, timing data for 27 debris flows and 2 rock slides, data from sediment collected at debris-flow headscarps and deposits, and Figures DR1–DR3, is online at www.geosociety.org/pubs/ft2014.htm. You can also request a copy from *GSA Today*, P.O. Box 9140, Boulder, CO 80301-9140, USA; gsatoday@geosociety.org.

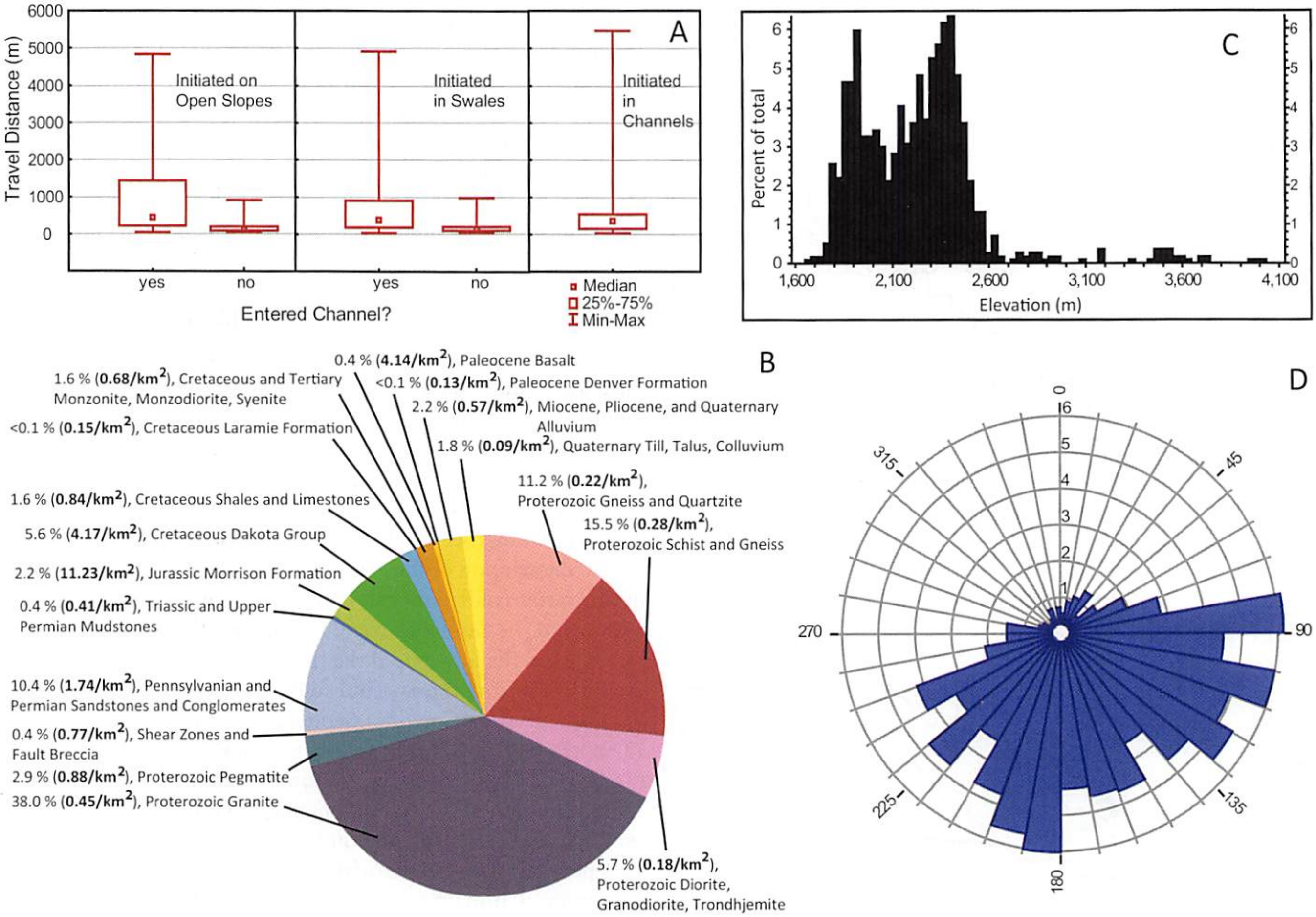

Figure 3. Characteristics of debris flows. (A) Box and whisker plots showing travel distance data, grouped by planform morphology at headscarps, and whether or not the flows entered channels. (B) Pie chart showing distribution of headscarps by geologic unit. Percentage of total number of flows and areal concentrations (bold) are shown. Flows in Paleocene Basalt were in quarry spoil. (C) Histogram of elevations of headscarps. (D) Rose diagram showing slope aspect at headscarps. Numbers on circles are percentages of total.

open slopes (48%) and swales (49%), with the remaining 3% initiating in channels (Fig. 3A). Debris-flow travel distances did not vary substantially between open slopes and swales, but were strongly influenced by the flows' interaction with channels. Flows that initiated in or entered channels traveled at least five times farther than flows that did not interact with channels (Fig. 3A). Field observations immediately after the event indicated that this effect was related to the availability of surface water and readily erodible sediment in channels as compared to hillslopes. Both of these factors enhanced sediment entrainment, debris-flow volume, and travel distance.

Debris flows initiated in colluvial soils formed on essentially every geologic unit in the Front Range (Fig. 3B). Seventy-three percent of debris flows initiated from soils on Proterozoic crystalline rock units. However, because these units encompassed a large percentage of the overall study area, the areal concentration of debris flows was low, ranging from 0.18 to 0.88 debris flows/km². Younger sedimentary units that form the hogbacks at the range front had a much lower total percentage of debris flows, but higher areal concentrations. For example, the Morrison Formation had the highest concentration of debris flows (11.23/km²) in the study area. Debris flows on the Morrison Formation initiated near the contact with the younger Dakota Group (Fig. 1B), reflecting differences in soil properties that influenced rainfall infiltration and shallow groundwater flow. Results from 18 grain-size analyses of soil from debris-flow headscarps and deposits indicate that the Morrison Formation has distinctly finer-grained soils (loam and sandy loam, Fig. DR2 and Table DR2) compared to other geologic units (sand and loamy sand, Fig. DR2).

Debris flows occurred across a wide range of elevations from 1650 m to 4050 m (Fig. 3C), although most flows were located lower than the widespread erosion surface at elevations <2600 m in the grassland and montane ecological zones. Debris flows occurred in about equal amounts above and below 2300 m, indicating that this previously identified threshold (Costa and Jarrett, 1981) should not be used to differentiate varying levels of debris-flow hazard. Recent wildfire burn areas in the montane zone (burns from 2000 to 2012, Fig. 1) were only slightly more susceptible to debris flows (0.35 debris flows/km²) than non-burn areas (0.28 debris flows/km²). This similarity in susceptibility is in contrast to the dramatic increase in debris-flow susceptibility typically observed in the first 2–3 years after a fire (e.g., Cannon et al., 2011). The apparent discrepancy likely is because all of the burn areas had at least one growing season to establish grass and other herbaceous vegetation before the storm; this partial recovery made the burn areas more similar in susceptibility to unburned, but sparsely vegetated slopes. The 10-year-old Overland burn area, which is now predominantly grass covered, accounted for 70% of all burn area debris flows (e.g., Fig. 1C), due in part to its close proximity to the area of highest cumulative rainfall (Fig. 1).

Slope aspect played a critical role in controlling debris-flow locations. Seventy-eight percent of debris flows initiated on south-facing slopes and another 6% initiated on east-facing slopes with azimuths from 80 to 90° (Fig. 3D). The strong south-facing control was not due to a bias in favor of south-facing slopes in the study area (Fig. DR3). Although the strong south-facing control is consistent with previous work on debris-flow frequency in the Front Range (Coe et al., 2003), the exact reasons for such control are unclear. Field observations indicate that south-facing slopes lack thick tree cover and have an abundance of rock outcrops compared to north-facing slopes. We expect that soils would also be thinner on south-facing slopes (e.g., Sidle and Ouchai, 2006), but this assumption has yet to be demonstrated in the Front Range. Another possibility is that the north- and westward-moving storm produced more intense rainfall on south- and east-facing slopes. Unfortunately, the positions of rain gages operating during the storm were inadequate to address this question.

## IMPLICATIONS FOR DEBRIS-FLOW HAZARDS

Our results have important implications for debris-flow hazards in the Front Range and for general debris-flow forecasting. Assessments of debris-flow hazards typically analyze two key factors: frequency and magnitude (volume, velocity, and travel distance). Relative frequency is often expressed in the form of susceptibility maps. In the Front Range, the well-defined topographic and geologic characteristics of debris flows shown in Figures 3 and DR1 should be used to create debris-flow susceptibility maps. In the grassland and montane ecological zones, the preferentially susceptible zone consists of steep, south- and east-facing hillslopes with small upslope contributing areas. In the subalpine and alpine zones, steep slopes with a wider range of upslope contributing areas define the susceptible zone.

The strong influence of slope aspect on controlling debris-flow locations is one of the more intriguing results from our study. A key currently unanswered question concerns differences in expected debris-flow magnitudes from south- versus north-facing slopes. We did not find a significant difference in the size of flows from south- and north-facing slopes in this study, but our sample of flows from north-facing slopes was small. An equally important question concerns the amount of rainfall (or snowmelt) required to generate widespread debris flows from north-facing slopes. Clearly, the exceptional rainfall in September 2013 was inadequate. Wildfire may be the key ingredient required to increase the susceptibility of north-facing slopes to debris flows.

For general debris-flow forecasting, the Front Range event serves as an alert to government authorities, emergency responders, and residents in interior continental areas with steep (>25°) slopes. Debris flows in these areas (i.e., where they occur infrequently) may pose a greater risk than in areas with shorter return periods because the public is less aware of and unprepared for them. For example, debris flows along the west coast of the United States (e.g., the Coast Range of Oregon) occur locally every year and are widespread about every 10 years. This frequency is short enough such that government agencies plan for the hazard and issue warnings in the most susceptible areas. This is not the case in the Front Range or elsewhere in the interior continental United States, where return periods for widespread debris-flow events are on the order of 50 years or more. A risk analogy can be drawn to the New Madrid seismic zone in the central United States, where earthquakes occur infrequently. There, recent research and educational campaigns have led to a greater understanding of the hazard and an increased level of public awareness. A similar effort is needed for debris flows in interior continental areas.

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