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Alpine debris flows triggered by a 28 July 1999 thunderstorm in the central Front Range, Colorado

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Abstract

On 28 July 1999, about 480 alpine debris flows were triggered by an afternoon thunderstorm along the Continental Divide in Clear Creek and Summit counties in the central Front Range of Colorado. The thunderstorm produced about 43 mm of rain in 4 h, 35 mm of which fell in the first 2 h. Several debris flows triggered by the storm impacted Interstate Highway 70, U.S. Highway 6, and the Arapahoe Basin ski area. We mapped the debris flows from color aerial photography and inspected many of them in the field. Three processes initiated debris flows. The first process initiated 11% of the debris flows and involved the mobilization of shallow landslides in thick, often well vegetated, colluvium. The second process, which was responsible for 79% of the flows, was the transport of material eroded from steep unvegetated hillslopes via a system of coalescing rills. The third, which has been termed the "firehose effect," initiated 10% of the debris flows and occurred where overland flow became concentrated in steep bedrock channels and scoured debris from talus deposits and the heads of debris fans. These three processes initiated high on steep hillsides (>30°) in catchments with small contributing areas (<8000 m^2), however, shallow landslides occurred on slopes that were significantly less steep than either overland flow process. Based on field observations and examination of soils mapping of the northern part of the study area, we identified a relation between the degree of soil development and the process type that generated debris flows. In general, areas with greater soil development were less likely to generate runoff and therefore less likely to generate debris flows by the firehose effect or by rilling. The character of the surficial cover and the spatially variable hydrologic response to intense rainfall, rather than a threshold of contributing area and topographic slope, appears to control the initiation process in the high alpine of the Front Range. Because debris flows initiated by rilling and the firehose effect tend to increase in volume as they travel downslope, these debris flows are potentially more hazardous than those initiated by shallow landslides, which tend to deposit material along their paths.

Keywords: Colorado; Front Range; Alpine environment; Debris flow; Rainfall; Topography; Alpine soils; North American Monsoon

1. Background and introduction

Sediment transport rates above timberline in the Front Range of Colorado are relatively low compared to other mountain environments and are dominated by rockfall, talus, and debris flow processes (Caine, 1986; Menounos, 1996). Debris flows, rapid gravity-driven mass flows of grains and intergrannular fluid (Varnes, 1978; Iverson and Vallance, 2001), are an important sediment transport process and natural hazard in high alpine environments (e.g. Caine, 1976; Costa and Jarrett, 1981; Rapp and Nyberg, 1981; Rickenmann and Zimmermann, 1993; Becht et al., 2005). In contrast to more temperate settings

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where debris flows are typically generated from landslide failure of the soil mantle (Campbell, 1975; Iverson et al., 1997), debris flows in the alpine are frequently initiated by the erosion and entrainment of hillslope and channel material by overland flow (e.g. Fryxell and Horberg, 1943; Curry, 1966; Berti et al., 1999; Hürlimann et al., 2003). Sediment entrainment by overland flow has been shown to be the dominant mechanism for debris flow generation in steep terrain burned by wildfire (Wohl and Pearthree, 1991; Meyer and Wells, 1997; Cannon et al., 2001a), and in poorly vegetated arid (David-Novak et al., 2004) and semi-arid landscapes (Griffiths et al., 2004).

Theoretical understanding of sediment transport under steady rainfall conditions (Dietrich et al., 1992; Montgomery and Foufoula-Georgiou, 1993) and empirical evidence from soil-mantled landscapes in temperate humid climates (e.g. Montgomery and Dietrich, 1994a; Vandaele et al., 1996) indicate that topographic form controls the spatial location of channel initiation. These findings have been used to partition the landscape into dominant channel initiation (saturation excess overland flow or shallow landslide) processes using a threshold relation between topographic slope angle and contributing area (Dietrich et al., 1992; Montgomery and Dietrich, 1994b). Similar topographic thresholds have been used in areas burned by wildfire to identify the initiation of debris flow transport (Cannon et al., 2001b). However, because debris flow generation by runoff processes is in part dependent on the availability of adequate material for transport (Bovis and Jakob, 1999), the topographic thresholds tend to vary with spatial variation in rock type and weathering intensity (Cannon et al., 2003).

The purpose of this case study is to document the debris flow activity associated with a 28 July 1999 thunderstorm in a 240-km^2 area roughly centered on the Continental Divide (Fig. 1). Overland flow and landslide processes triggered about 480 debris flows that were concentrated on the flanks of Mount Parnassus, on the western flanks of Lenawee Mountain and Grizzly Peak near the Arapahoe Basin Ski area, and the northern flank of Torreys Peak (Fig. 1). Field examination of debris flows and comparison of initiation locations with digital topography and soils mapping of the northern part of the area indicates that most runoff debris flows were initiated on steep slopes where bedrock is shallow or exposed at the ground surface. Landslide debris flows were initiated on significantly less steep slopes in thick colluvium often with well-developed soils and vegetal cover. A detailed map showing the debris flow source areas and deposits was published previously and is available online (http://pubs.usgs.gov/of/2003/ofr-03-050/, Godt and Coe, 2003).

The debris flows did not cause any fatalities or injuries, but Interstate Highway 70 (I-70) and U.S. Highway 6 (U.S. 6) were blocked for about 25 h disrupting traffic on the major east–west routes through the mountains. Impacts to property were largely confined to the Arapahoe Basin ski area where about US$200,000 in damage to facilities was reported (Henceroth, 2000; Coe et al., 2002). We begin this paper with a description of the physiographic and geologic setting of the study area and follow with an analysis of the triggering rainfall. We then discuss our observations of debris flow initiation processes and their correlation with surficial cover type and present grain-size analyses of colluvium in debris flow source areas and of debris flow deposits. We conclude with results from an analysis of the topography of debris flow source areas and evaluate these source areas in the context of previously proposed topographic thresholds for channel initiation. Our hope is that the baseline information presented in this paper can be used in future regional modeling efforts to assess debris flow hazard.

1.1. Physiographic and geologic setting

The study area is located about 50 km west of Denver, CO in the central Front Range (Fig. 1) and is underlain predominantly by Precambrian biotitic gneiss and quartz monzonite with scattered Tertiary intrusions (Lovering, 1935; Bryant et al., 1981), which have undergone varying degrees of hydrothermal alteration and mineralization (Tweto and Sims, 1963). Much of the area is in the alpine zone, defined here as the area above timberline (∼3500 m elevation). Vegetative cover is primarily coniferous forest below timberline. Above timberline, hillside surfaces either are covered with alpine tundra or are unvegetated bedrock and colluvium. No glaciers or permanent snowfields are located in the study area; however, the highest north-facing slopes may hold snow well into the late summer. Elevations in the study area range from about 2900 m in the valley of Clear Creek to nearly 4350 m at the summit of Grays Peak (Fig. 1). The terrain is characterized by glaciated valleys and unglaciated interfluves (Barsch and Caine, 1984; Madole et al., 1998). The unglaciated interfluves are generally either bedrock arêtes or low-relief ridges capped by a bouldery diamicton that may be remnants of Tertiary-age alluvium and debris flow deposits (Madole, 1982). The area was glaciated several times during the Pleistocene, but only three ages of glacial deposits can be distinguished. Ice of the most recent glaciation (Pinedale age) descended to an elevation of about 2500 m in the Clear Creek valley. Pinedale ice is estimated to have disappeared between 14,000 and 12,000 ^{14}C years BP